Volume 51 May 1956 Number 3

Economic Geology

and the

Bulletin of the Society of Economic Geologists

CONTENTS

Uraniferous Magnetite-Hematite Deposit at the Prince Mine, Lincoln County, New Mexico ..... *George W. Walker and Frank W. Osterwald* 213

Geochemistry of Sphalerite from the Star Mine, Coeur d'Alene District, Idaho ..... *Verne C. Fryklund, Jr. and Janet D. Fletcher* 223

The Paragenesis of Accessory Minerals ..... *W. W. Moorhouse* 248

The Alteration of Ilmenite in Beach Sands ..... *S. W. Bailey, E. N. Cameron, H. R. Spedden, and R. J. Weege* 263

Scientific Communications:

The Taconite Deposits in the Mount Wright Area of Quebec ... *George Vibert Douglas* 280

A Modern Definition of Ore ..... *Bahngrell W. Brown* 282

Discussions:

Concentration of Uranium by Carbon Compounds ..... *John W. Gruner* 284

Copper Deposits of the Lake Superior Region ..... *T. M. Broderick* 285

Reviews:

Erzlagerstätten (Hans Schneiderhöhn) ..... *Chas. H. Behre, Jr.* 288

Geology and Oil Resources of the Rose Hill and Jonesville Districts, Lee County, Virginia (Miller, Fuller and Brosgé) ..... *John E. Sanders* 289

Géologie du Congo belge (L. Cahen) ..... *Jean Bérard* 292

Les Lacunes des Cristaux et leurs Inclusions Fluides (G. Deicha) ... *Horace Winchell* 294

Water, The Yearbook of Agriculture 295

Stratigraphic Geology (M. Gignoux) 295

Man and the Winds (E. A. de la Rue) 295

The North American Midwest 296

Books Received ..... *Kurt Servos* 296

Scientific Notes and News 300

PUBLISHED SEMI-QUARTERLY

Six Dollars Fifty Cents a Year, One Dollar Twenty-five Cents a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

Manuscripts for publication should be sent to the Editor, **ALAN M. BATEMAN, at Yale University, Yale Station, New Haven, Conn.** It is requested that contributors exercise care in writing *scientific* and *proper names*. References to other publications should be in accordance with the forms used in the pages of this journal. The manuscript should be typewritten with double space lines and must be preceded by *a brief abstract*. Galley proof will be sent authors only where a request to this effect accompanies the manuscript, or when, in the editor's opinion, the subject matter is such as will require correction by the author.

Reviews should conform to the journal usage. Review Committee: The Editor, C. H. Behre, L. C. Graton, J. T. Singewald, Jr., J. Gilluly, A. F. Buddington, W. H. Newhouse.

Books and Pamphlets for review should be sent to the Editor.

Reprints. Contributors desiring reprints of their papers may obtain them by filling out the order slip which will be attached to the galley proof when it is sent to the author. Provided the order slip is received by the editor, *with the return of the proof*, 50 reprints without covers will be furnished without charge. Reprints of discussions and informal communications are not furnished free of charge except when they exceed four pages in length when 50 will be supplied without charge. Reprints of reviews are not supplied. Additional reprints will be furnished at approximately the rates given in the table below (effective with No. 5) when ordered *in advance of publication*. The rates apply only to plain text, with line engravings. Papers containing folded maps or plates will be more expensive.

The following rates do not include free carriage. ***Postage or express must be paid by the author.***

	4 pp. 1–4	8 pp. 5–8	12 pp. 9–12	16 pp. 13–16	20 pp. 17–20	24 pp. 21–24	28 pp. 25–28	32 pp. 29–32	Covers
50 copies.....	$4.20	$6.65	$10.40	$10.85	$14.15	$16.25	$18.70	$19.95	$5.75
100 "	5.00	7.95	12.00	13.30	17.00	19.95	23.30	25.00	7.80
Additional copies per C.	1.70	2.55	4.20	5.00	5.85	7.50	9.15	10.00	3.75

For 500 copies deduct 5%; for 1000 copies or more deduct 10%. For more than 32 pages add cost per schedule to make total. Example: For 44 pages add cost for 32 pages and 12 pages. The 50 copy price is the minimum charge.

Covers: Standard covers are of the same style of type and paper as the cover of the journal, and bear the title of the article and name of its author. Special printing on cover is charged for at the cost of composition.

Plates are $4.20 for the first 50 if printed on one side, and $3.15 per "C" for additional's; printed on both sides, $6.30 for the first 50, and $4.70 per "C" for additional's.

Collotype plates are 8 cents each for each additional reprint over the 50 copies furnished free. Example: An extra 50 reprints containing one collotype plate would cost $4.00; 2 collotype plates, $8.00.

Note: For any reprints requiring additional composition or changes, either in text or cover, an extra charge will be made.

The retail prices of single reprints when available from the office of the Business Manager are as follows:

1–4 pp. 15c	5–8 pp. 20c	9–12 pp. 25c	13–20 pp. 30c	21–28 pp. 35c
29–36 pp. 40c	37–44 pp. 45c	45–52 pp. 50c	53–60 pp. 55c	61–68 pp. 60c

Subscriptions. The price of the journal to subscribers in the United States and its dependencies is $1.25 for a single copy, or $6.50 a year for eight numbers effective July 1, 1953. To subscribers in Canada, Cuba, Mexico, Spain, and countries in Central and South America, except Dutch and French Guiana, the annual rate is $6.80; to other countries, $7.25.

Forwarding. Subscribers wishing their journal to be forwarded to a new address should leave postage for that purpose with the Postmaster at their old address.

Missing numbers will be replaced without charge if claim is made within four weeks after the date of issue of the following number, provided that the neglect to receive them is not due to neglect to arrange for their forwarding.

Remittances should be made payable to the **ECONOMIC GEOLOGY PUBLISHING COMPANY**, and should be mailed to **M. M. LEIGHTON**, Business Manager, Urbana, Illinois, to whom also all **Business Communications** should be addressed.

Foreign Agents. The Technical Bookshop, Salisbury House, London Wall, London E. C. 2, England, British Agents.

Indexed in the Industrial Art Series.

LANCASTER PRESS, INC., LANCASTER, PA.

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

ASSISTANT EDITORS

H. E. MCKINSTRY, *Harvard University*
M. LEROY JENSEN, *Yale University*
JOE W. PEOPLES, *Wesleyan University*
J. D. BATEMAN, *Toronto, Ont.*
R. H. JAHNS, *California Institute of Technology, Pasadena*

ASSOCIATE EDITORS

CHARLES KENNETH LEITH
Madison, Wisconsin

D. F. HEWETT
U. S. Geological Survey, Pasadena, Calif.

A. I. LEVORSEN
Tulsa, Okla.

B. S. BUTLER
Univ. of Arizona, Tucson, Ariz.

W. E. WRATHER
U. S. Geological Survey, Washington, D. C.

A. N. SAYRE
U. S. Geological Survey, Washington, D. C.

L. C. GRATON
Orange, Connecticut

E. S. MOORE
Univ. of Toronto, Toronto, Can.

PER GEIJER
Djursholm, Sweden

P. F. FOURMARIER
Liège University, Liège, Belgium

M. S. KRISHNAN
Geological Survey, Calcutta, India

T. W. GEVERS
University of the Witwatersrand, Johannesburg, S. Africa

C. F. DAVIDSON
Geological Survey, London, England

J. A. BROGGI
Instituto Geologica, Lima, Peru

TAKEO WATANABE
University of Tokyo, Tokyo, Japan

A SEMI-QUARTERLY JOURNAL PUBLISHED BY
THE ECONOMIC GEOLOGY PUBLISHING COMPANY

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1956

FRANCIS CAMERON, *President*

HENRY C. GUNNING, *Vice President*

OLAF N. ROVE, *Secretary*, 30 East 42nd Street, New York 17, New York

JOSEPH T. SINGEWALD, JR., *Treasurer*, Johns Hopkins University, Baltimore 18, Maryland

Councilors

1956	*1957*	*1958*
RICHARD M. FOOSE	R. F. BAKER	F. S. TURNEAURE
W. R. LANDWEHR	JOHN W. VANDERWILT	DONALD M. FRASER
HUGH M. ROBERTS	THOMAS L. KESLER	CHARLES MEYER

Regional Vice Presidents

PAUL RAMDOHR, Europe.....JORGE A. BROGGI, South America
J. AUSTEN BANCROFT, Africa.....JENARO GONZALEZ-REYNA, North America
HAROLD G. RAGGATT, Australia.....TAKAO SAKAMOTO, Asia

Executive Committee

FRANCIS CAMERON, *Chairman* — HENRY C. GUNNING — GILBERT H. CADY
JOSEPH T. SINGEWALD, JR. — OLAF N. ROVE

President's appointments to Committees for 1956–57

Finance Committee

DONALD M. FRASER, *Chairman* — ROBERT P. KOENIG
JOSEPH T. SINGEWALD, JR. — OLAF N. ROVE, *Ex-officio*

Program Committee

ARTHUR J. BLAIR, *Chairman* — ERNEST L. OHLE
CHARLES H. BEHRE, JR. — CHARLES F. PARK, JR.
DONALD M. DAVIDSON — ADOLPH E. SANDBERG
THOMAS E. GILLINGHAM — OLAF N. ROVE, *Ex-officio*

Committee on Publications

OLAF P. JENKINS, *Chairman* — GEORGE B. LANGFORD — CHARLES MEYER

Nominating Committee

RAYMOND F. BAKER, *Chairman* — J. D. BATEMAN — JOHN W. VANDERWILT

Admissions Committee

C. PHILIP JENNEY, *Chairman* — E. N. PENNEBAKER — EDWARD SAMPSON
PHILLIP L. MERRITT — F. S. TURNEAURE

Auditing Committee

FRANCIS G. WELLS, *Chairman* — A. NELSON SAYRE

Coal Research Committee

ELSO S. BARGHOORN, *Chairman* — PAUL AVERITT
CLAYTON G. BALL — GILBERT H. CADY

ORDER BLANK

FIFTIETH ANNIVERSARY VOLUME
ECONOMIC GEOLOGY
1905-1955

(See page ii)

☐ Enclosed is $..... ☐ Enter my order and send bill

☐ Price to Subscribers $6.00

(including Members, Non-Member Journal Subscribers, and Students whether subscribers or not)

☐ Price to Non-Subscribers to Journal $8.00

To Economic Geology Publishing Company
105 Natural Resources Building
Urbana, Illinois

Mail above copy as checked to:

Name

Street Address

City State Country

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 51 MAY, 1956 NO. 3

URANIFEROUS MAGNETITE–HEMATITE DEPOSIT AT THE PRINCE MINE, LINCOLN COUNTY, NEW MEXICO[1]

GEORGE W. WALKER AND FRANK W. OSTERWALD

CONTENTS

	PAGE
Abstract	213
Introduction	213
Geologic setting	215
Uraniferous magnetite-hematite deposit	215
Origin of deposit	218
Conclusions	221
References	222

ABSTRACT

A pyrometasomatic magnetite-hematite deposit in sedimentary rocks of Permian age near the margin of the Lone Mountain stock in Lincoln County, N. Mex., contains between 0.015 percent and 0.031 percent uranium. The deposit is composed mainly of magnetite with lesser amounts of hematite, hydrated iron oxides, pyrite, leuchtenbergite(?), gypsum, chalcopyrite, metatorbernite, torbernite(?), covellite, sphalerite (?), quartz, marcasite, and an unidentified uranium-bearing mineral; it is surrounded by an aureole of recrystallized limestone, gypsum, epidote, and actinolite with lesser amounts of specularite, phlogopite, fluorite, pyrite, and chalcopyrite. Autoradiographs and polished section studies suggest that most of the uranium is dispersed in the iron oxide minerals. The association of iron and uranium may be related to the melting points of the elements. The deposit probably formed at a rather low temperature by self-oxidation of a ferrous hydroxide hydrosol contained in a mildly alkaline solution.

INTRODUCTION

THIS paper presents briefly some data concerning an association of uranium with magnetite and hematite in a pyrometasomatic deposit in Lincoln County, N. Mex., and presents some aspects of the genesis and the distribution of uranium in the deposit. The data were obtained through a brief examination of the deposit in February 1954 and through subsequent laboratory studies

[1] Publication authorized by the Director, U. S. Geological Survey.

of a few representative samples collected during the examination. This report concerns work done by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

The deposit, known at various times as the Carolyn O claim, House mine, Las Cinco Reinas, and more recently as the Prince mine, is in sec. 14, T. 6 S., R. 11 E., White Oaks district, and is about 11.5 miles N 30° E of Carrizozo, N. Mex. (Fig. 1). It is on the north side of Lone Mountain at an altitude estimated at about 6,700 feet. The magnetite-hematite body occurs in a sequence of sedimentary rocks probably of Permian age and is assumed to be genetically related to the Lone Mountain monzonite stock. Uranium is present in the deposit in two distinct forms: 1) metatorbernite, and possibly some torbernite, as fracture coatings and pore space fillings, and 2) a finely divided, unidentified uranium-bearing mineral dispersed through magnetite and locally in primary crystalline hematite.

Minor quantities of ore containing approximately 60 percent iron (13) have been extracted from open pits; a 200-foot adit, driven on a south bearing, tested part of the ore horizon at depth. Under economic conditions

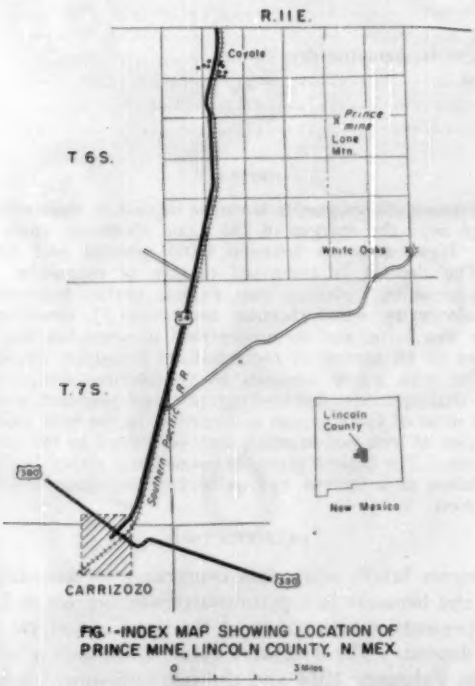


FIG. 1. Index map showing location of Prince mine, Lincoln County, N. Mex.

existing in 1955 neither iron nor uranium are present on the property in commercially significant quantities.

GEOLOGIC SETTING

The Prince deposit is in a series of bedded sedimentary rocks composed of alternating gypsum, shaly limestone, quartzitic sandstone, and shale that, according to Kelley (5, p. 157), are part of the Yeso formation of Permian age. The deposit is near the periphery of the Lone Mountain monzonite stock of Laramide age.

The sedimentary rocks, which commonly are buff, are bleached to light buff or white near the ore body and are characterized by beds ranging from an inch to about 2 feet thick. Adjacent to the deposit the beds are steeply dipping and locally highly contorted; the deposit apparently is conformable with the bedding.

The Lone Mountain monzonite stock crops out less than 100 feet south of the Prince deposit. The stock and several other nearby hypabyssal intrusives in Lincoln County were emplaced during the Laramide Revolution of Late Cretaceous or early Tertiary time. Adjacent to the contact with the Yeso formation, the monzonite is a pinkish-gray, medium- to fine-grained rock that locally is porphyritic. A thin section of the monzonite is composed of orthoclase (about 60 percent), sodic andesine (about 30 percent), hornblende, sphene, magnetite, and minor amounts of quartz, apatite, biotite, nontronite(?), and clinozoisite(?). Some of the plagioclase shows a normal, continuous zonation with rims of sodic oligoclase; many of the plagioclase and orthoclase crystals have thick overgrowths of cloudy orthoclase. Most of the hornblende crystals are ragged, highly corroded, and poikilitic, and they contain grains of sphene and magnetite. Sparse biotite is similarly corroded. Texturally, in thin section, the rock is dominantly hypidiomorphic-granular although protoclastic and cataclastic textures are discernable. According to some rock classifications this intrusive rock would be named a syenite rather than a monzonite as the alkalic feldspar predominates over the calc-alkalic feldspar at a ratio of approximately 2 to 1, and quartz is present only in very minor amounts.

An aureole, locally as much as 6 feet thick, of bleached and altered material adjacent to the deposit is composed of recrystallized limestone, gypsum, and an assemblage of lime-silicate minerals of which the most abundant are epidote and actinolite. Also present in the aureole are minor amounts of specular hematite, phlogopite, fluorite, pyrite, and chalcopyrite. The fluorite and the sulfide minerals occur principally as ill-defined veinlets and as disseminations in the rocks of the aureole.

URANIFEROUS MAGNETITE-HEMATITE DEPOSIT

The uraniferous magnetite-hematite deposit at the Prince mine is tabular and parallel to the bedding and is exposed in a series of pits for a strike length of nearly 100 feet; the maximum width is about 6 feet. The wall rocks

adjacent to the magnetite-hematite mass show local, but strong fracturing. Later and more widespread faulting has fractured the magnetite-hematite body, which apparently replaced a limestone bed or lens in a section composed largely of gypsum.

Finely granular but massive magnetite is the dominant constituent of the deposit. Present in lesser quantities are massive hematite, specular hematite, hydrated iron oxides, pyrite, a chloritelike mineral (estimated $2V = 18°$; $\beta = 1.58 \pm 0.05$; $n_a - n_\gamma = 0.014 \pm$, which is suggestive of leuchtenbergite), gypsum, minor chalcopyrite, sparsely distributed crystals of metatorbernite (and possibly some torbernite) on fracture surfaces, covellite, an unidentified uranium-bearing mineral, sphalerite(?), quartz, marcasite, and one observed grain of questionably identified galena. Disseminated grains of pyrite and minor chalcopyrite in the iron ore commonly form a megascopically distinct reticulate pattern. Semiquantitative spectrographic analyses (Table 1) of three samples of the magnetite-hematite body indicate that, in addition to iron, the only other metallic element present in amounts exceeding a fraction

TABLE 1

SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSES OF SAMPLES FROM THE PRINCE MINE, LINCOLN COUNTY, N. MEX.[1]

Sample[2]	Si	Al	Fe	Ti	Mn	Ca	Mg	Na	K
1	.x+	.x+	xx.	.0x−	.x−	.x	x.−	.0x	.x+
2	.x	.x	xx.	.0x−	.x−	.x+	x.−	.0x+	.x+
3	.x	.x	xx.	.0x−	.x	.x−	x.−	Tr	0

	Ba	Be	Ce	Co	Cr	Cu
1	.00x−	.000x	.x	.00x+	.00x	.0x−
2	.00x−	.000x−	.x	.00x+	.00x	.0x−
3	.000x	.000x	.0x	.00x+	.00x	.0x−

	Ga	La	Mo	Nb	Nd	Ni	Pb	Sc	Sr
1	.00x−	.x−	.00x	.00x	.0x+	.00x	Tr	.00x	.00x+
2	.00x−	.x−	.00x−	.00x	.0x+	.00x	.00x−	.00x	.00x+
3	.00x−	.0x	.00x−	.00x	.0x−	.00x−	.00x	0	.00x−

	V	Y	Zn	Zr
1	.00x+	.0x−	.0x	.00x−
2	.00x	.0x−	.0x	Tr
3	.00x	.00x+	.0x	.00x−

Looked for but not detected: P, Ag, As, Au, B, Bi, Cd, Dy, Er, Gd, Ge, Hf, Hg, In, Ir, Li, Os, Pd, Pt, Re, Rh, Ru, Sb, Sn, Sm, Ta, Th, Tl, Te, U, and W.

0 = Looked for but not detected.
Tr = Near threshold amount of element.

[1] Analyst: R. G. Havens, U. S. Geological Survey.
[2] Sample 1—Continuous chip sample across width of magnetite-hematite body.
Sample 2—Radioactive magnetite and hematite containing relatively abundant sulfide minerals.
Sample 3—Magnetite-hematite specimen with metatorbernite on joint surfaces.

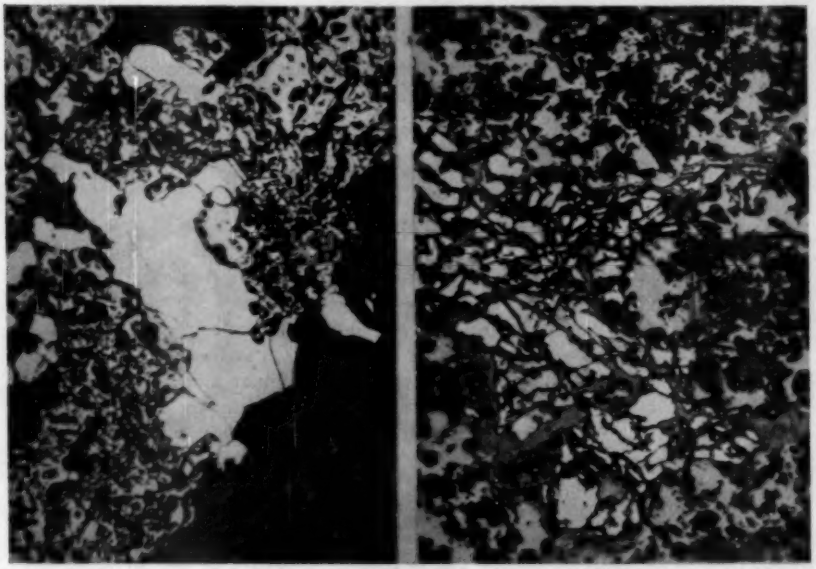
of a percent is magnesium, probably largely in the chloritelike mineral but possibly in magnesite or substituting for Fe^{++} in the magnetite. Radioactivity and chemical analyses for uranium of these samples gave, respectively, 0.023, 0.016, 0.044 percent equivalent uranium and 0.015, 0.012, 0.031 percent uranium.

A few veinlets of calcite, quartz, hematite, and an unidentified white chalcedonic material, suggestive of highly siliceous magnesite, cut both the wall rocks and the magnetite-hematite body.

Brief study of a few polished sections and autoradiographs of specimens of the iron ore suggest that the iron oxide minerals and the sulfide minerals were deposited separately and that the primary uranium was deposited only with the magnetite and hematite. In polished section, primary crystalline hematite is intergrown with magnetite and, less commonly, occurs as microscopic veinlets on interfaces between crystals of magnetite. Pyrite crystals occur as nearly equidimensional subhedra, as extremely irregular and embayed grains that commonly contain inclusions of magnetite, hematite, or other minerals, and as crushed crystals with some fractures filled with magnetite and hematite (Fig. 2). Most of these fractures are confined to pyrite crystals and only a few extend into the bounding magnetite. The chalcopyrite in the iron deposit is present largely as inclusions in pyrite; a few irregular covellite grains are bound by thin rims of sphalerite(?) which, in turn, are bounded either by magnetite or hematite or both. The uranium—exclusive of that in secondary uranium-bearing minerals, which coat fractures and fill pore spaces—is in minute, unidentified particles rather uniformly distributed in the magnetite and, locally, in the crystalline hematite; autoradiographs show that the uranium-bearing mineral is absent in the sulfide minerals and is sparse where the magnetite is in contact with sulfide crystals (Fig. 3). Some thin veinlets of supergene hematite and limonite cut most of the constituent minerals of the iron ore.

Although pyrite and minor chalcopyrite are locally distributed in the iron ore in a megascopically reticulate pattern that suggests localization in preexisting structures in the magnetite-hematite body, study of polished sections indicates that some sulfide mineral grains are extensively replaced by magnetite and hematite, some contain inclusions of magnetite, and others are highly fractured whereas the magnetite is not. Conceivably the magnetite and sulfide minerals could be essentially contemporaneous; however, because of the distinctly different types of pyrite crystals, it is thought that there were two distinct periods of sulfide mineralization separated by an intervening period of iron oxide mineralization in which only sparse sulfides were deposited. The distribution of the unidentified, uranium-bearing mineral indicates that it was deposited with the magnetite and hematite, and accordingly it is inferred that it is genetically related to the same pyrometasomatic activity that introduced the magnetite.

The sulfide minerals and fluorite in the aureole adjacent to the ore body are not appreciably radioactive although the fluorite is the deep purple variety commonly associated with uranium in other deposits.



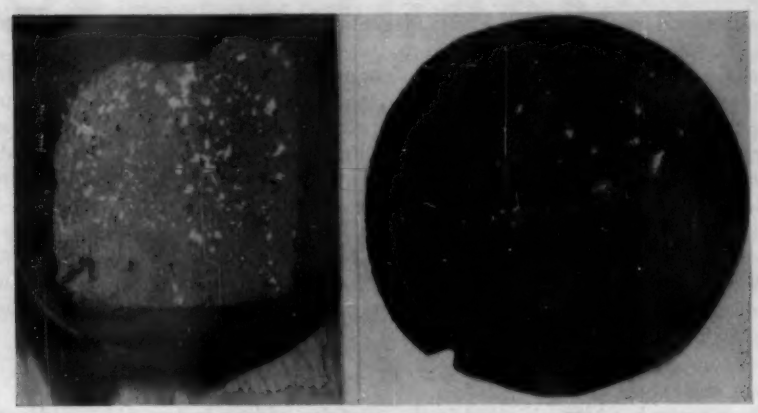
2a. 2b.

FIG. 2. Polished sections of two iron-ore specimens from Prince mine, Lincoln County, N. Mex. a. (left) Pyrite (white) embayed and replaced by magnetite and hematite. 41 ×. b. (right) Fractures in pyrite (white) filled with magnetite and hematite. 94 ×.

ORIGIN OF DEPOSIT

The uraniferous magnetite-hematite deposit at the Prince mine is interpreted to have formed pyrometasomatically as a replacement of sedimentary rocks adjacent to a monzonite pluton. Uranium was introduced during the oxide phase of mineralization but not during the sulfide phase.

Although all the genetic implications of this iron-uranium association are not clearly understood, these elements probably were mobilized and concentrated through energy derived from a magma now represented by the monzonite. Sullivan (14) has suggested that similarity of melting points of elements may have a considerable significance in metallic associations in ore deposits. Because the melting points of iron and uranium are relatively close (respectively 1535° C and 1150° C; 14, Table 1), the iron and uranium at the Prince mine originally may have been mobilized and concentrated more or less simultaneously. Conceivably both elements were primary constituents of the monzonite magma and were extracted at about the same time from the crystallizing melt. On the other hand, they may have been extracted from the invaded rocks, either through assimilation of wall rock or diffusion of these substances into the magma, possibly concentrated, and deposited in their present environment. Present surface exposures of the monzonite are



3a. 3b.

FIG. 3. Polished section and autoradiograph of iron-ore specimen from Prince mine, Lincoln County, N. Mex. a. (left) Polished section of magnetite-hematite ore with layers containing pyrite (white). Diameter of polished section mount is 1.24 inches. b. (right) Autoradiograph of same polished section showing distribution of uranium-bearing materials. Large white spots show location of metatorbernite and torbernite(?) crystals.

not abnormally radioactive, although the monzonite may contain trace amounts of uranium in the relatively abundant accessory magnetite. Other uranium-bearing minerals were not observed in thin sections.

Although finite temperature and pressure conditions cannot be established for the mineralizing process that introduced iron and uranium, the temperature is thought to have been relatively low because: (1) The contact-metamorphic aureole enclosing the ore body is relatively thin, and (2) the aureole is composed, in part, of relatively low-temperature contact-metamorphic minerals rather than high-temperature contact-metamorphic minerals such as garnet and pyroxene. The physical and mineralogic character of the aureole may be more largely dependent, however, on the composition and volume of the silicating solution, the permeability of the country rock, and the relative pressure gradient at time of mineralization rather than temperature; the paucity of quartz suggests that these solutions may have contained only moderate amounts of silica. The epidote in the aureole may serve as a rough indicator of the temperature at which the aureole formed. Epidote probably forms between 300° and 500° C (4, p. 1088), and the Prince ore body probably was formed within or only slightly above that range. The sulfide minerals and fluorite in the aureole, as well as some of the pyrite and chalcopyrite in the deposit, were introduced by lower temperature hydrothermal solutions that followed the higher temperature pyrometasomatism.

The field evidence suggests that the iron deposit may be a rather clear example of a process outlined by Shand (11) for the origin of certain mag-

netites and related ores. Many magnetite deposits have been ascribed to residual solutions rich in iron (1, p. 410–412), but Shand (12, p. 191–192) believes that many such residual solutions are alkaline and do not contain dissolved iron. Such solutions from crystallizing magmas are postulated to be relatively enriched in sodium and potassium ions and thus have an alkaline reaction. The intrusive rocks near the Prince mine are rich in feldspar and, hence, were probably formed from a mildly alkaline magma; residual solutions were probably also alkaline. Shand believes the solutions contain a hydrosol of ferrous hydroxide, kept in suspension by the alkalies. His belief is supported by the fact that ferrous hydroxide is insoluble in alkaline solutions. With the extraction of the alkalies in the solution, the hydrosol undergoes self-oxidation, forming magnetite, water, and free hydrogen, according to the following equation:

$$3Fe(OH)_2 = Fe_3O_4 + 2H_2O + H_2 \uparrow$$

The process has been observed in the corrosion of iron boilers (11), and one of the authors has observed black magnetic powder, possibly magnetite, formed in marine engine boilers operated at about 300° to 400° C, at 215 pounds pressure per square inch.

The coagulation of such a hydrosol would be aided by $MgSO_4$ or $K_2Cr_2O_7$ as electrolytes in the solution (6, p. 685). Table 1 shows that the ore has an appreciable amount of Mg and a little Cr; the sulfate ion could have been extracted from the gypsum in the Yeso formation and potassium ion could have been available from the residual magmatic solution.

This hypothesis of origin provides a good answer for two questions raised by Bateman (1, p. 404 and 426) about the formation of late magmatic oxide ores: (1) "If concentrations of heavy ferromagnesian silicates are formed in the lower portions of intrusives then why not also similar concentrations of iron and titanium oxides?", and (2) " . . . why such difficultly meltable substances as magnetite and ilmenite should remain in the residuum of a basic magma and how can they remain molten to permit injection?".

The process of uranium deposition may be similar to that postulated for deposits near Schmiedeberg in the Riesengebirge by Berg (2) and Meister (7). Magnetite deposits in a skarn zone were affected by late-stage solutions from a granitic magma that deposited copper, lead, zinc, and silver sulfides, oxidized magnetite to hematite, and deposited pitchblende around pieces of hematitized magnetite. Botryoidal pitchblende is partly replaced by sulfides. In the Schmiedeberg deposits, the Prince mine, and probably elsewhere, uranium is closely associated with iron oxide and not with sulfide minerals. As uranium at the Prince mine principally is associated only with magnetite and hematite, it is inferred that it was fixed during the oxide phase of mineralization rather than the sulfide phase; primary uranium is conspicuously absent in all the sulfide minerals and is not associated with them, though some secondary crystals of metatorbernite do occur in open spaces in fractured pyrite.

The physico-chemical factors involved in the fixing of uranium in this

type of environment are not clearly understood, although it is apparent that the iron and the uranium were introduced at essentially the same time. Probably some, and perhaps all, of the primary uranium occurs as an impurity in the interstices of the magnetite lattice; it seems likely that the cerium, lanthanum (Table 1), and possibly other elements, are similarly trapped in the magnetite lattice. The uranium and rare earths also may occur as a rare earths-uranium mineral perhaps comparable to davidite. The even distribution of the uranium in the iron oxide may be the result of coprecipitation during the coagulation of the hydrosol. Most uranium compounds are slightly more soluble than the corresponding iron compounds and, according to Pierce and Haenisch (9, p. 312), this should aid the coprecipitation of uranium with an iron hydrosol. The coagulation must have taken place at a relatively low temperature, or the iron hydroxide would have been purified, and uranium expelled. Higher temperature causes coprecipitated ions to be released and is commonly used in laboratories to purify precipitates. The association of uranium with the iron oxide phase in the ore and not with the sulfide phase may be caused by the differences in the sols of the two phases. According to MacDougall (6, p. 686), metals and metallic sulfides form negatively charged sols in systems with water as the dispersion medium, whereas the sols of metallic hydroxides are positively charged. It may be that uranium was in the form of positively charged particles, which were coprecipitated with the oxides and not with the related sulfides in the Prince mine ore.

The exact manner in which the uranium is contained in the iron oxide minerals at the Prince mine is not known. It is unlikely that magnetite contains actual segments of the uraninite structure because uraninite has a face-centered cubic lattice (8, p. 611), whereas magnetite has an octahedral-tetrahedral type of structure (3, p. 98–101). However, the spinel (magnetite) lattice can accommodate many different ions (3, p. 98), and uranium—in sixfold coordination—could probably substitute for Zn, Cu, or Cd in the lattice, according to its ionic radius (10, p. 794–795).

CONCLUSIONS

At the Prince mine, uranium is associated with pyrometasomatic magnetite and hematite thought to be genetically related to monzonite intruded into sedimentary rocks of Permian age. Both the iron and uranium are thought to have been mobilized and concentrated at essentially the same time by energy derived from a magma now represented by the monzonite. Both elements may have been primary constituents of the monzonitic magma, or they may have been extracted from the invaded rocks. The uranium, which was fixed during the oxide phase of mineralization and not during the sulfide phase, is present in some unidentified form probably, in part, substituting for Zn, Cu, or Cd, in the spinel (magnetite) lattice. It is thought that the uranium and the iron oxide were coprecipitated during the coagulation of a hydrosol of ferrous hydroxide in a mildly alkaline environment and under relatively low-temperature conditions. The magnetite in the Prince deposit probably re-

sulted from self-oxidation of a ferrous hydroxide hydrosol during extraction of alkalis from solution.

U. S. GEOLOGICAL SURVEY,
DENVER, COLO.,
Jan. 16, 1956

REFERENCES

1. Bateman, A. M., 1951, The formation of late magmatic oxide ores: ECON. GEOL., v. 46, no. 4, p. 404–426.
2. Berg, Georg, 1936, Die Eisenlagerstätte von Schmiedeberg im Riesengebirge: Zeitschr. Prakt. Geologie, Berlin, v. 44, p. 193–198.
3. Bragg, W. L., 1937, Atomic Structure of Minerals: Cornell University Press, Ithaca, New York, 292 p.
4. Harpum, J. R., 1954, Formation of epidote in Tanganyika: Geol. Soc. America Bull., v. 65, p. 1075–1092.
5. Kelley, V. C., 1949, Geology and economics of New Mexico iron-ore deposits: Univ. of New Mexico Pub. in Geology, illus., 246 p.
6. MacDougall, F. H., 1947, Physical Chemistry: Macmillan Co., New York, 722 p.
7. Meister, E., 1926, Uber ein neues Vorkommen von Uranpecherz auf der Bergtreiheitgrube in Schmiedeberg im Riesengebirge: Zeitschr. Prakt. Geologie, Berlin, v. 34, p. 44–45.
8. Palache, Charles, Berman, Harry, and Frondel, Clifford, 1944, The System of Mineralogy of James Dwight Dana and Edward Salisbury Dana, 7th ed., v. I: John Wiley & Sons, Inc., New York, 834 p.
9. Pierce, W. C., and Haenisch, E. L., 1940, Quantitative Analysis, 2nd ed.: John Wiley & Sons, Inc., New York, 462 p.
10. Rankama, Kalervo, and Sahama, Th. G., 1949, Geochemistry: University of Chicago Press, Chicago, 911 p.
11. Shand, S. J., 1947a, The genesis of intrusive magnetite and related ores: ECON. GEOL., v. 42, no. 7, p. 634–636.
12. Shand, S. J., 1947b, Eruptive Rocks, 3rd ed.: John Wiley & Sons, Inc., New York, 488 p.
13. Sheridan, M. J., 1947, Lincoln County iron deposits, New Mexico: U. S. Bur. Mines Rept. of Inv. 3988, 19 p.
14. Sullivan, C. J., 1954, Metallic melting point and ore deposition: ECON. GEOL., v. 49, no. 6, p. 555–574.

GEOCHEMISTRY OF SPHALERITE FROM THE STAR MINE, COEUR D'ALENE DISTRICT, IDAHO[1]

VERNE C. FRYKLUND, JR. AND JANET D. FLETCHER

CONTENTS

	PAGE
Abstract	223
Introduction	224
Reasons for choice of Star mine, and sample collection	224
Resume of Star mine geology	225
General geochemical considerations	226
Geothermometry of Coeur d'Alene district sphalerite	228
Preparation of samples and methods of spectrographic analysis	232
Results of analyses	233
Correlation of Fe content of sphalerite with position in ore shoot	238
Correlation of minor elements of sphalerite with position in ore shoot and with formation temperatures	241
Comparisons with other studies of minor elements in sphalerite	242
Factors that determined concentration of minor elements in Coeur d'Alene sphalerite	245
Conclusions	245
Acknowledgments	246
References	246

ABSTRACT

Forty sphalerite samples from the Star mine, Coeur d'Alene district, Idaho, and 19 sphalerite samples from other Coeur d'Alene mines have been quantitatively analyzed by spectrographic methods for Fe, Cu, Pb, Cd, Ga, Ge, In, Mn, Co, and Hg. The samples from the Star vein were collected over a strike length of 2,000 feet and a vertical distance of 5,300 feet.

It is believed that Star mine sphalerite formed in equilibrium with Fe; consequently, following Kullerud's work, the Fe content may be used as a relative temperature scale. Relative Fe temperatures suggest that the lower portions of the Star ore body formed at lower temperatures than the upper portions of the ore body.

Distribution of the minor elements in sphalerite is random within the ore body. Also, there is no correlation of Fe with minor elements other than Mn; therefore we believe temperature has had no influence on the distribution of minor elements, except Mn, in this ore body.

The principal reason for this seems to be that equilibrium concentrations of the minor elements were not reached. Minor-element concentrations in sphalerite from the Coeur d'Alene district are similar to those in other districts throughout the world; consequently, the writers suggest that in general the minor-element content of sphalerite, other than per-

[1] Publication authorized by the Director, U. S. Geological Survey.

haps Mn, cannot be an indicator of formation temperatures because equilibrium concentrations are rarely, if ever, attained.

The average minor-element content in a district is probably that of the ore-forming solutions. Specific minor-element content in sphalerite is random.

INTRODUCTION

THE U. S. Geological Survey is investigating the ore deposits of the Coeur d'Alene district. The geochemistry of sphalerite, a major ore mineral in the Coeur d'Alene district, has been studied in some detail, emphasis being placed on the variation of iron, to be considered a major element of sphalerite, and on the minor-element content. Fe is a major constituent of most Coeur d'Alene sphalerite, and it was hoped that the variation in Fe content, reflecting temperature conditions, would assist in determining the origin and manner of deposition of the ore deposits in the district. Minor-element content of sphalerite also was investigated because of the economic importance of several minor elements and the hope that the abundance and distribution of minor elements might also aid in determining the origin of the ore deposits.

The literature of geochemistry includes a number of spectrographic studies of sphalerite (5, 6, 7, 9, 11, 12, 13, 17, 18, 20, and 24). As far as the writers are aware, however, no studies have been made of sphalerite from a single ore shoot, or detailed studies of sphalerite from a single large ore district. This paper mainly presents the results of a study of the Star mine ore body from which samples were collected over a strike length of 2,000 feet and over a vertical distance of 5,300 feet. The study of Star mine sphalerite should be considered as only a reconnaissance because of the relative sparseness of sample pattern. Forty samples from the Star mine were analyzed; 19 samples from other mines in the Coeur d'Alene district were analyzed, and the results are included here.

Reasons for Choice of Star Mine, and Sample Collection.—The objective of this part of the sphalerite study was the investigation of the geochemistry of sphalerite from a single large vein. It is quite possible that such a study should first be done on a fissure vein; however, the veins in the Coeur d'Alene district are, with the possible exception of the gold-scheelite and stibnite veins, replacement veins. It was thought that if an ore shoot had been formed over a large range of temperatures such a range would be most pronounced in a large ore shoot and that any differences in sphalerite chemistry resulting from a range of formation temperatures could then be more readily recognized.

A desirable vein for such a study, of course, should have complete accessibility over a long strike length and over a great vertical range. The Star mine, primarily a zinc mine, was selected for sampling because it most nearly fitted these qualifications. Only half of the very large ore shoot lies within the boundaries of the Star mine; the remainder, in the Morning mine, is now inaccessible. The upper part of the Star mine is accessible from the 1,000 to the 2,900 level, and the lower part of the mine from the 4,700 to the 5,500 level. In time, part of the ore shoot below the 5,500 level of the mine will be accessible and this study can then be extended. In addition, samples were

collected on the Morning mine 5,200 level, which will be equivalent to the Star mine 6,800 level. The Morning-Star ore shoot was incompletely studied, and owing to closing of the Morning mine in 1953, that portion of the vein will remain so; however, parts of the now inaccessible vein and its ore have been described by Ransome (16), Umpleby and Jones (21), and Waldschmidt (23).

Mining in the Star mine, and the Coeur d'Alene district in general, is done by square-set stoping followed closely by filling floors with waste. At any given time sampling must be restricted to accessible levels and to those parts of the vein being mined and it is, therefore, impossible to sample an ore body at any given time in the detail desired.

Samples for analysis were chosen to be as uniformly distributed as possible throughout the ore shoot in the Star. Some parts though, could not be sampled because of their inaccessibility. Also some of the samples collected were discarded because the sphalerite within them was too intimately intergrown with magnetite or pyrite to make a clean separation possible.

RESUME OF STAR MINE GEOLOGY

The Star mine is at Burke, Idaho, in the northern part of the Coeur d'Alene district. The main portal is connected by a long crosscut to the deposit about 2 miles to the south. The general geology of this area (north half of the Mullan, Idaho, Special Sheet) has been described by Ransome and Calkins (16), Umpleby and Jones (21), and Griggs (10). The country rock of the Coeur d'Alene district consists of slightly metamorphosed, quartzitic to argillitic sediments of the Precambrian Belt series that have been folded, faulted, and intruded by granitic stocks and dikes of various types. The Belt series in the district consists, from bottom up, of the Prichard, Burke, Revett, St. Regis, Wallace, and Striped Peak formations. The series has an exposed total thickness of 23,000 feet.

The Morning-Star vein, except for the great size of its ore shoot, is typical of the veins in the Coeur d'Alene district. It is the result of an extensive series of replacements (16, 21). The earliest vein-forming fluids introduced minerals that formed veins by replacing country rock along faults and shear zones, whereas the later fluids deposited minerals that replaced both country rock and earlier vein minerals.

The Star mine is on the western half of an ore shoot on the Morning-Star vein; the other half is in the Morning mine. The strike of the Morning-Star vein is irregular, but the portion in the Star mine trends in general about N. 79° W. The over-all dip is about 85° N. The ore shoot has a maximum stope length of 4,000 feet; the known pitch length is 6,300 feet. Within the Star mine the vein is in massive beds of the Revett quartzite, which have a general steep dip to the northeast. The vein in the eastern part of the Morning mine cuts the overlying more argillaceous St. Regis formation.

The paragenetic sequence of the major minerals present is, approximately: pyrite (oldest ?), magnetite, siderite, ankerite, barite, sphalerite, chalcopyrite, and galena. Minor minerals include: chlorite, marcasite (younger than

colloform pyrite and older than sphalerite), quartz, tetrahedrite, and a late ruby silver, probably polybasite. Thermal metamorphism of the vein by a large lamprophyre dike has formed silicates from country rock, quartz, and siderite.

Estimation of the pressure during vein formation is handicapped by the difficulty in estimating the amount of cover removed by erosion since Late Cretaceous time when the veins were probably formed, plus the added uncertainty as to the amount of post-mineral dip-slip movement on the Osburn fault. The senior writer believes that dip-slip movement of at least 2,500 feet accompanied strike-slip movement of about 16 miles.

The writers are assuming that the lowest known ore north of the Osburn fault formed at a depth of 14,500 feet. Assuming a system open to the surface, minimum hydrostatic pressure, pre-erosion, on the lowest known ore would have been about 365 atmospheres. Minimum rock pressure at the same point would have been about 1,185 atmospheres, assuming 76 atmospheres for each 1,000 feet of rock. The temperature due to the normal geothermal gradient at 14,500 feet would set the lower limit of temperature of sphalerite formation. Assuming a geothermal gradient of 1° centigrade per 100 feet, the minimum temperature 14,500 feet below the surface would be 145° centigrade.

GENERAL GEOCHEMICAL CONSIDERATIONS

In a limited study of this type, the principal geochemical problems to consider might be grouped under two headings: (1) what minor elements substituted for Zn in Coeur d'Alene sphalerite; (2) what factors determined a particular concentration of a minor element in Coeur d'Alene sphalerite. Only problems that come under the first heading will be considered in this section, and even then it will be necessary to anticipate some of the results of latter sections.

According to Haberlandt (11) minor elements in a mineral may be there because: (1) the element is part of the mineral structure; (2) the element may have been trapped in micro-openings of one kind or another; (3) the element may have been adsorbed on the surface of the mineral at some time; (4) the element may be present as a major component of a foreign mineral inclusion, or, in one of the three previously mentioned ways, as a minor element in an inclusion. Thus, it seems that modes are available for any element to be present in a given mineral sample.

The term "minor element" in reference to a mineral, however, is probably generally understood to mean an element that is occupying a position in the mineral structure that normally would be occupied by a major component of the mineral, and in amounts detectable by present spectrographic methods. A major problem, of course, is: how does one determine that the element in question is occupying such a position in the particular mineral structure? It appears that without a synthesis one can only indicate the possibility of substitution—that it is permissive.

There is of course a considerable literature that describes crystal chemical

criteria of permissiveness with respect to substitution where the ionic bond is involved, but unfortunately all this seems to have but slight application where covalent and metallic bonding is concerned. Many writers have discussed the problem; Schroll's (17) discussion is a good example.

The writers, and probably most other investigators of minor elements, have used a combination of empirical and crystal chemical data that include: (1) the likelihood that the element in question is not in an inclusion of a mineral known to be in a district, as shown by an examination of polished surfaces; (2) the fact that no mineral containing major amounts of the element is known to exist in nature; (3) crystal chemical data relating to artificial compounds; (4) tables of ionic and covalent radii; (5) gross chemical dissimilarity of the minor constituent and the element supposedly being replaced; and (6) records of previous analyses that show a group of elements common to a particular mineral. There is no doubt, however, that an answer to the question as to whether an element can actually substitute for another element, particularly where the covalent bond is important, depends upon an analysis of the bonding by wave mechanical methods.

Some other sphalerite analyses from other districts (6, 13) seem to show that sphalerite generally contains only a limited number of elements other than Zn and S. These elements commonly include Fe, Cd, Mn, Ga, Ge, In, Co, and Hg that, the writers believe, substitute for Zn in Coeur d'Alene district sphalerite. Kullerud (12) has synthesized sphalerite with varying amounts of Fe, Mn, and Cd and has shown how unit cell dimensions were affected by those elements. There is then no question that Fe, Mn, and Cd can substitute for Zn. There appear to have been no syntheses of sphalerites rich in other minor elements so that a decision as to whether they should or should not be considered as substituting for Zn must be based on other considerations. Ga and In are not known to be essential constituents of any mineral (15, p. 720) and as their tetrahedral covalent radii are of appropriate size, Ga—1.26 A, In—1.44 A (14, p. 179), undoubtedly the two elements substitute for Zn, with a covalent radius of 1.31 A (14, p. 179). Ge is a constituent of an exceedingly rare group of minerals, and it is doubtful if the Ge reported in sphalerite analyses from the Coeur d'Alene, or other, districts is in inclusions of argyrodite, for instance. Hg has been reported in tetrahedrite from the Coeur d'Alene district, but in quantities less than 0.01 percent. No other Hg-bearing mineral is known in the district. The material analyzed was not contaminated by tetrahedrite, so the writers believe that Hg also substitutes for Zn in Coeur d'Alene district sphalerite. No attempt to recover this mercury is made.

Co probably substitutes for Zn in Coeur d'Alene sphalerite. Gersdorffite is found in the Coeur d'Alene Silver Belt, but is apparently confined to this zone, and no other cobalt-nickel minerals have been recognized in sphalerite from other parts of the district. Of interest is the small tonnage of cobalt recovered each year from sludges at the Sullivan Mining Company's electrolytic zinc plant (22, p. 449) from dominantly Coeur d'Alene district zinc concentrates.

Cu and Pb were determined in order to check on the purity of the samples, and to make appropriate corrections in the Fe values. Cu is present as chalcopyrite, and a portion of the Fe value must be alloted for chalcopyrite (completely insignificant amounts of some of the minor elements were probably also contributed by chalcopyrite).

The writers, then, are confident that Fe, Mn, Cd, Ga, Ge, Hg, In, and Co substitute for Zn in Coeur d'Alene sphalerite, but they are not so certain about the role of Ag or the distribution of all the Cu. Eleven semi-quantitative analyses were made during the course of the quantitative spectrographic determinations (Table 4). Ag was detected in all but one sample—a single crystal—but the occurrence of Ag presents unsolved problems in that neither Sb nor As were detected in any of the semi-quantitative analyses, which might eliminate a ruby silver or other sulfosalt as the source of the Ag; the spectrographic sensitivities of Sb and As, however, are much inferior to that of Ag. Possibly Ag is present as unidentified argentite or native silver; more likely much of the Ag is in galena inclusions. Some Cu may substitute for Zn, as has been shown possible by Buerger (2). Such substitutions would compensate for the extra electric charges introduced by Ga and In, but undoubtedly most of the Cu, and possibly most of the Ag, values represent inclusions.

Other elements reported in the semi-quantitative, and quantitative, analyses are Ca, Sn, Mg, Al, Ba, Ti, Ni, Sr, Zr, and V. Ni may actually substitute for Zn; Sn may also, or it may be in cassiterite as in some Canadian sphalerite (24); Ca and Mg are undoubtedly in carbonate inclusions (some Mn also); Ba and Sr are undoubtedly in barite inclusions; Al, Ti, Zr, and V are probably constituents of country-rock inclusions.

The list of elements looked for but not detected in the semi-quantitative analyses is of interest as the list indicates that sphalerite may, in general, commonly contain only a select group of minor elements. The analyses of Oftedal (13), where he analyzed both sphalerite and galena from a number of deposits, certainly shows this to be true. Analyses in Table 3 of two sphalerite crystals and a galena crystal from the same vug tend to confirm this. Cd and Co were restricted to sphalerite; Bi and Sb were restricted to galena. Unfortunately, Ge, Ga, and Hg were not detectable in the material analyzed.

GEOTHERMOMETRY OF COEUR D'ALENE DISTRICT SPHALERITE

When this study was started it was hoped that the minor-element distribution, combined with the known fact that the Fe content of sphalerite increases with the temperature of formation (4), would at least roughly indicate temperatures of formation in the Star ore shoot. Very fortunately during the course of the investigation Kullerud (12) published the FeS-ZnS phase diagram and thus placed our work on a much more firm basis.

Donald H. Richter of the U. S. Geological Survey attempted to check temperatures of formation by optical observations of bubble inclusions and the decrepitation technique. Only a very minor amount of Coeur d'Alene sphalerite, however, is sufficiently transparent to permit observation of

bubble inclusions, and such sphalerite comes from veins formed later than the major productive stage. The results of the decrepitation work are presented in Table 1 (Table 1, Decrepitation temperatures of selected sphalerite specimens).

According to Richter (written communication), "from these results then, it appears that sphalerite, regardless of its iron content and/or formation temperature, decrepitates between 295 and 340° C. Like calcite and other rhombohedral carbonates it is probably not suitable for study by the decrepitation technique."

It would appear that, at present, the determination of temperatures of formation of sphalerite will depend largely on Kullerud's FeS-ZnS phase diagram.

The FeS–ZnS system has been determined by Kullerud (12, p. 64) who states: "Provided sufficient iron sulfide was present during the formation of the mix-crystals, the ZnS would dissolve an amount of iron determined by the temperature and pressure conditions existing during the formation of the sulfides."

"In numerous ore deposits pyrrhotite occurs intimately connected with sphalerite (marmatite). From geological studies it has been shown that an abundance of iron was generally present during the entire process of ore formation. Therefore, in such cases one may safely assume that equilibrium conditions existed between free pyrrhotite and the FeS dissolved in the sphalerite lattice at the time of sphalerite formation. In any sample of sphalerite fulfilling the above mentioned conditions, the amount of FeS dissolved is related to the temperature of formation of mix-crystals. Hence, the temperature of ore deposition, disregarding pressure, may be determined from the amount of FeS dissolved in the sphalerite lattice using the FeS–ZnS diagram."

Further, (12, p. 109), "It may now be concluded that the FeS solubility in ZnS is not very sensitive to a variation in the S:Fe ratio in pyrrhotites and

TABLE 1

DECREPITATION TEMPERATURES OF SELECTED SPHALERITE SPECIMENS

Sample No.	Fe (wt. percent)	Decrepitation temp. C.
VCF–377a–53	4.0*	318[4]
VCF–185g–52	2.9[1]	307[4]
VCF–185i–52	0.58*	306[4]
VCF–185h–52	0.42*	296[4]
RE–152	0.5	310
RE–258	0.5	295–315
RE–337	0.5	322–340
RE–164	[3]	325–330
TWS–27	[3]	334

* Spectrographic analysis.
[1] Chemical analysis.
[2] Dark honey color, probably near 0.5 Fe also.
[3] Colorless to light honey color. Probably almost pure ZnS.
[4] Average decrepitation temperature.

is only slightly (2 percent) decreased when pyrite (FeS_2) forms mix-crystals with ZnS. Consequently the diagram may be used as a geologic thermometer also where FeS_2 is found in equilibrium with (Fe, Zn) S mix-crystals.

However, if such a situation exists in nature, the diagram presented can not be used where sulfur is present in excess of the amount needed to satisfy the FeS_2 formula."

The boundary between the β(Fe, Zn)S field and the FeS–β(Fe, Zn)S field of the phase diagram should be, therefore, of considerable geologic interest. Kullerud has made the tacit assumption that the shape and position of this solid solvus curve would not be greatly affected by the presence of minor constituents. The writers are willing to make the same assumption, but would like to point out that the literature of metallography is replete with examples of binary systems whose solid-state fields can be drastically altered by small amounts of a third component, but perhaps not in the minute quantities common to many minor elements.

Even if it could be satisfactorily demonstrated that a naturally occurring sphalerite formed in an environment where there was an excess of Fe, it seems doubtful that the temperatures of formation deduced from study of the artificial system FeS–ZnS can be applied to sphalerite from an ore deposit. A major difficulty in using the Fe content of the sphalerite to indicate the precise temperature of formation is that no information is available on the system FeS–ZnS–H_2O. Water was surely a major component of the ore-forming solutions. Judging from its behavior in other systems, the presence of water is likely to have a considerable effect on the FeS–ZnS solvus line. The temperatures determined from Kullerud's data may therefore not give an absolute scale to apply to an ore deposit. It seems unlikely, however, that the presence of water could change the relations in such a way that more Fe could be taken into sphalerite at low temperatures than at high temperatures.

We may be justified then for a particular ore deposit to indicate relative formation temperatures by an Fe temperature scale. For example, a sphalerite containing 3 percent Fe could safely be considered as forming at a lower temperature than one containing 6 percent Fe. The writers throughout the remainder of this paper have assumed that a particular Fe content indicates a particular temperature, provided it is possible to demonstrate that the sphalerite in question was in equilibrium with Fe when it formed. This assumption is believed to be quite justified, and of course it puts discussions of temperature control of minor-element occurrence on a completely different, and we believe firmer, basis than heretofore.

Equilibrium with Fe during formation is somewhat difficult to prove, but there is considerable evidence that most of the sphalerite from the Star mine, and other mines listed in Table 2, formed in reasonably Fe-rich environments; quite possibly Fe was available in excess of that needed for equilibrium at formation temperatures.

The only way to demonstrate that there was equilibrium with respect to

Fe for a particular sample during formation depends first on showing that excess Fe is still present in another Fe-bearing mineral, and second, on what one can see at the contact between the sphalerite and the Fe-bearing mineral.

The Coeur d'Alene veins are replacement veins, and in the Star mine unreplaced remnants of magnetite, pyrite, marcasite, and siderite, as well as ankerite, all Fe-bearing, are in sphalerite, frequently in considerable quantities.

Sphalerite from most parts of the Star mine, in thin section, is uniform in color (and Fe-content) even where it is in contact with Fe-rich minerals.

We think it reasonable to assume that during the formation of sphalerite that has partially replaced magnetite, for instance, an excess of Fe was present. The color of sphalerite is largely dependent upon its Fe content and if the color of sphalerite near, or at, its contact with magnetite is similar in color to sphalerite away from the contact, as observed in thin section, it is apparent that there is no Fe concentration gradient. We would judge, first of all, that the sphalerite at the contact was in equilibrium with Fe at the time it formed; and second, that the sphalerite farther away from the contact was also in equilibrium with Fe when it formed. Most of the sphalerite, in the Star or other Coeur d'Alene district mines, in contact with Fe-bearing minerals shows no color differences.

A more useful example might be a situation where it is possible to show that non-equilibrium conditions with respect to Fe have occurred. Such examples are probably not rare but they are sufficiently uncommon to make one suspect that much naturally occurring sphalerite formed in equilibrium with Fe. If no other Fe-bearing phase is present, of course, it would be as impossible to prove dis-equilibrium as it would be to prove equilibrium; if, however, sphalerite is in contact with an Fe-bearing mineral and one can show that sphalerite at the contact contains more Fe than the same sphalerite mass 2 to 3 mm away from the contact, we believe it safe to say that most of the sphalerite at one time was not in equilibrium with Fe.

This situation has occurred at sphalerite contacts with Fe-rich minerals in the contact zone adjacent to a nearly vertical lamprophyre dike exposed in the Star mine from the 1,000 level to the 5,100 level. This dike, about 50 feet wide, has thermally metamorphosed adjacent portions of the vein. At contacts between sphalerite and Fe-rich minerals, principally magnetite but also pyrite and siderite, Fe has diffused into the sphalerite, producing dark ruby-red (as seen in transmitted light) rims 0.02 to 0.03 mm wide, strongly contrasting with the amber-colored main sphalerite masses. These reaction rims are present only in sphalerite adjacent to the dike, and they occur in thin sections of samples taken from several different levels.

To recapitulate, the lack of reaction rims in most sphalerite at contacts between sphalerite and Fe-rich minerals indicates that the Fe in the sphalerite was in the equilibrium with Fe in the Fe-rich mineral when the sphalerite formed. Reheating the sphalerite at the contact with a dike, presumably well above formation temperature, has permitted a solid-state reaction in which Fe has moved into the sphalerite.

PREPARATION OF SAMPLES AND METHODS OF SPECTROGRAPHIC ANALYSIS

Samples selected for analysis were crushed several times, contaminating material being removed after crushing. Massive sphalerite was abundant, and it was not necessary to up-grade material by heavy-liquid separations. Final picking of approximately 35- to 60-mesh material was made using a binocular microscope. Separation of magnetic fractions was made at all stages with an Alnico magnet. If the very fine-grained impurities were chalcopyrite or galena, a reasonable attempt was made to remove the material, but as Cu and Pb were determined, it was not necessary to reject such samples. Previous studies had indicated that galena does not contain the minor elements commonly found in sphalerite. Chalcopyrite may contain some of the minor elements present in sphalerite, but the amounts contributed by included chalcopyrite (note Cu values in Table 2) would be close to, if not below, the limits of detection. The possible exception would be sample number 54–6205 that contained 1 percent Cu; in this case perhaps some Co was contributed by chalcopyrite. If the specimen contained very fine-grained magnetite or pyrite, as determined in polished sections, that could not be liberated by crushing to picking size, the sample was discarded.

The general method used for the spectrographic analysis of geological materials has been previously described (8) so only the steps required to adapt it for the analysis of sphalerites will be described. All of the sphalerite samples were powdered and initially diluted with an equal weight of a mixture consisting of 90 percent quartz and 10 percent sodium carbonate. This mixture was incorporated in the samples in order to improve their burning qualities in the d.c. arc. If from this initial exposure, the calculated results for the elements looked for, namely Fe, Cu, Ge, Pb, Cd, In, Mn, Ga, and Co showed a high concentration, further dilution was indicated. This dilution consisted of mixing with the samples varying amounts of a pegmatite-base mixture consisting of 60 percent quartz, 40 percent feldspar, and 1 percent Fe_2O_3. Since the regular standards in the Geological Survey's spectrographic laboratory have as their matrix this pegmatite-base mixture, the incorporation of this mixture with the samples reduced the matrix difference between samples and the standards, and brought the concentration of the various elements within the accurate range of the analytical working curves. Sphalerites analyzed chemically for Fe were exposed along with the samples and served to validate our analytical curves for Fe.

The regular analytical procedure was not suitable for determining Hg because of the extreme volatility of the element. The results were erratic and were considered to be too high. Oftedal (13) has shown that the spectrum of Hg is considerably more intense when the element is present as a solid-solution component of natural sphalerite than when it is present as prepared HgS mixed mechanically into a synthetic standard. He, therefore, utilized a chemically analyzed, Hg-rich sphalerite for preparing his standards. Such a sphalerite was not available for the present investigation.

The effects due to the extreme volatility of Hg are substantially reduced

if a separate determination is made for the element using the following modifications of the method.

Electrode crater: 15 mm depth, 4.7 mm diameter. The regular-grade electrode to be ignited at 600° C. for 10 min just prior to use in order to eliminate any contamination.
Sample size: 50 mg
Arc current: 9 amps
Exposure time: 15 secs with commensurate increase in the amount of light permitted to enter the spectrograph.

Both the initially prepared mixture of sphalerite and Na_2CO_3–quartz mentioned above and the pegmatite-base standards containing Hg as chemically precipitated HgS were exposed under the modified conditions. The more gradual release of Hg into the arc from the deep electrodes substantially reduced the differences in the intensity of the Hg lines due to differences in the mode of combination of the element. That this matrix effect was completely eliminated could not be verified because of the lack of sphalerites of known content of Hg. Although there is thus some uncertainty as to the absolute accuracy of the Hg percentages reported in Table 2, the relative differences among the samples were verified through replicate analyses.

Following is a list of the lines of the various elements determined and their sensitivities under the described working conditions:

Element	Wavelength A	Sensitivity Wt. %
Cu	3273.96	0.0002
Ge	2651.18	.002
Pb	2833.07	.002
Cd	3261.06	.01
In	3039.36	.003
Mn	2939.30	.04
	2949.20	.02
	2974.82	.0009
Co	3453.50	.001
	3449.17	.02
Fe	3175.45	2.0
	3286.76	.4
	3021.07	.002
Ga	2943.64	.001
Hg	2536.52	.0001*

* This sensitivity for Hg is only possible with the special procedure used for determining this element.

RESULTS OF ANALYSES

The results of quantitative analyses of 59 samples are presented in Table 2. Quantitative analyses of single crystals are presented in Table 3. The results of semi-quantitative analyses of 11 samples are presented in Table 4. The average concentrations for 59 analyses in Table 1 are shown in Table 5. Pb and Cu are considered to be impurities.

Although the number of analyses is few for the size of the mine, the differing Fe contents of sphalerite from the top and bottom of the mine can be

TABLE 2

SPECTROGRAPHIC ANALYSES OF SPHALERITE FROM THE COEUR D'ALENE DISTRICT, IDAHO
Analyses by Janet D. Fletcher unless otherwise noted

Lab. No.	Fe	Fe correc.	Cu	Ge	Pb	Cd	In	Mn	Ga	Co	Hg	Mine, Level
53–2020SW[1]	6.2	6.2	0.013	0.0015	0.12	0.46	0	0.58	0.0014	0.004	—	Star, 1,700
53–2021SW[1]	5.5	5.5	.016	.0017	.08	.37	0	.27	.0004	.004	—	Star, 2,700
53–2022SW[1]	5.5	5.5	.012	.0046	.29	.42	0	.33	.0014	.004	—	Star, 1,450
53–2023SW[1]	3.9	3.9	.013	.0017	.06	.65	0	.17	.0013	.002	—	Star, 2,100
53–2024SW[1]	6.2	6.2	.064	0	.42	.47	0	.32	.0010	.004	—	Star, 2,100
53–2025SW[1]	5.	5.	.025	.0017	.21	.63	.004	.21	.0010	.003	—	Star, 1,450
54–211S	4.	4.	.01	0	.23	.34	.003	.07	0	.003	—	Star, 2,700
54–212S	11.	11.	.1	0	.84	.34	0	.96	.0006	.005	0.01	Star, 4,900
54–213S	9.	9.	.3	.004	.72	.52	0	.96	.004	.005	—	Star, 1,200
54–214S	6.	6.	.008	.005	.18	.42	0	.24	.002	.004	.009	Star, 2,300
54–215S	8.	8.	.02	0	.74	.35	0	.17	.0005	.002	.007	Star, 2,300
54–216S	6.	6.	.1	.003	.80	.70	0	.42	.002	.003	—	Star, 2,700
54–217S	6.	6.	.02	0	.38	.60	0	.22	.001	.004	.02	Star, 2,700
54–457S	4.7	4.7	.016	0	.09	.23	0	.58	0	.004	.007	Star, 1,200
54–458S	2.9	2.9	.011	.004	.70	.40	.004	.35	.001	.004	.005	Star, 1,450
54–459S	3.1	3.1	.022	0	.23	.44	.004	.58	.003	.003	.01	Star, 1,450
54–460S	3.4	3.3	.14	.003	1.	.29	0	.26	.0009	.004	—	Star, 2,100
54–461S	6.7	6.6	.17	0	1.	.26	0	1.4	.001	.005	.007	Star, 1,700
54–462S	2.6	2.6	.014	0	.02	.36	.004	.04	0	.004	.008	Star, 1,700
54–463S	3.1	3.	.15	.002	.01	.44	0	.33	.002	.003	—	Star, 1,700
54–464S	3.1	2.7	.40	0	.19	.36	0	.21	.0007	.02	—	Star, 1,700
54–615S	3.5	3.35	.25	0	1.6	.35	0	.51	.001	.004	—	Star, 5,500
54–616S	3.5	3.5	.012	0	.004	.53	0	.28	.002	.005	—	Star, 5,500
54–617S	2.8	2.6	.2	0	.08	.29	.005	.27	.0007	.006	.01	Star, 1,200
54–618S	2.2	2.2	.049	0	.2	.34	0	.21	.0004	.005	.005	Star, 2,700
54–619S	2.2	1.85	.4	0	.2	.53	0	.10	0	.006	.02	Morning, 5,200
54–620S	1.4	0.5	1	0	.24	.54	0	.24	.0004	.039	—	Star, 2,700
54–621S	3.1	3.1	.024	0	.84	.49	0	.26	.0009	.004	—	Star, 4,900
54–622S	4.	4.	.0048	0	.84	.34	0	.70	.0006	.005	—	Star, 4,900
54–623S	2.8	2.8	.015	0	.25	.36	0	.35	.001	.004	.009	Star, 4,900

TABLE 2—*Continued*

Lab. No.	Fe	Fe correc.	Cu	Ge	Pb	Cd	In	Mn	Ga	Co	Hg	Mine, Level
54–139038	4.5	4.5	.047	0	.22	.36	.003	.07	0	.008	—	Star, 1,000
54–139039	5.	4.8	.18	0	.15	.50	.004	.58	.001	.004	—	Star, 1,000
54–139040	5.	5.	.088	0	.065	.48	.004	.58	.0008	.008	—	Star, 1,200
54–139041	4.6	4.5	.11	.002	.11	.80	.004	.26	.003	.004	—	Star, 5,100
54–139042	4.8	4.7	.076	0	.10	.40	.004	.48	.0007	.004	—	Star, 1,450
54–139044	3.7	3.6	.13	0	.14	.36	0	.06	.0006	.008	—	Star, 4,700
54–139045	4.6	4.6	.013	0	.002	.56	0	.06	0	.01	—	Star, 5,100
54–139046	3.9	3.9	.014	0	.01	.52	0	.19	.003	.005	.006	Star, 5,100
54–139047	3.4	3.4	.012	0	.01	.60	0	.18	.003	.005	—	Star, 5,100
54–139048	4.2	4.2	.054	0	.03	.46	0	.19	0	.008	—	Star, 5,100
53–1595	.34	.34	.01	0	.007	.41	0	.0009	0	0	—	Idaho, 200
53–160S	2.90*	2.90	.003	0	.004	.21	0	.06	.001	.003	—	Success, 1,100
53–161S	.42	.42	.006	0	.07	.20	0	.009	.001	.003	—	Success, 1,100
53–162S	.58	.58	.004	0	.04	.24	0	.007	.001	.003	—	Success, 1,100
53–163S	2.70	2.70	.003	0	.005	.24	0	.06	.001	.003	—	Success, 1,100
53–164S	3.2	3.2	.004	0	.05	.21	0	.03	.002	.009	—	Tamarack
53–165S	.72	.72	.002	0	.009	.16	0	.002	0	0	—	Big It, adit
53–166S	4.1	4.1	.002	0	.4	.15	0	.04	.0006	.007	—	Amazon, 2,000
54–832S	9.2	9.3	.0070	0	.44	.19	0	.1	0	.0074	—	Sidney, 900
54–833S	5.1	5.1	.013	.006	.004	.098	0	.07	.006	.010	—	Idaho, 300
54–834S	4.	4.	.0086	.006	.097	.38	0	.1	.002	.0090	—	Frisco, 2,400
54–835S	3.5	3.5	.011	.004	.01	.40	0	.06	.001	.002	—	Page, 2,100
54–836S	3.2	3.2	.013	.004	.02	.34	0	.06	.002	.002	—	Page, 3,000
54–837S	2.2	2.2	.0091	.002	.03	.45	0	.04	.002	.0072	—	Page, 2,700
54–838S	2.1	2.1	.012	.002	.097	.40	0	.05	.002	.0066	—	Page, 2,700
54–839S	4.	4.	.0044	0	0	.25	0	.01	0	.0059	—	Sunset, 800
54–139049	5.5	5.5	.0068	.002	.096	.28	.004	.06	.0008	.0009	—	H-Surprise No. 4 Adit
54–139050	4.8	4.8	.011	0	.11	.40	0	.32	.001	.003	—	Frisco, 1,400

* Chemical analysis by Leonard Shapiro.
[1] Spectrographic analyses by Harry Bastron.
0 Looked for but not found.
— Not looked for.

TABLE 3

SPECTROGRAPHIC ANALYSES OF SINGLE CRYSTALS FROM A VUG, 800 LEVEL, SUNSET MINE, COEUR D'ALENE DISTRICT, IDAHO*

	Fe	Fe correc.	Cu	Ge	Pb	Ag	Cd	In	Mn	Ga	Co	Rem
VCF-377a-53	4.0	4.0	0.0044	0	0	0	0.25	0	0.01	0	0.0059	Single crystal
VCF-377A-53 (Interior)	4.9	4.9	.003	0	.12	.0033	.2	0	.01	0	.0074	Inside of sphalerite crystal (¼ in.)
VCF-377A-53 (Exterior)	5.3	5.3	.003	0	.054	.0033	.2	0	.01	0	.0070	Outside of sphalerite crystal
Galena Crystal	.007		.0006	0	Major	.12	0	0	.0006	0	0	Galena crystal

Semi-Quantitative Analyses

Sample No.:	VCF-377a-53	VCF-377A-53 (Inside)	VCF-377A-53 (Outside)	Galena crystal
X0.%	Zn	Zn	Zn	Pb
X.	Fe	Fe	Fe	
.X	Cd	Cd, Pb	Cd	Bi, Sb, Ag
.0X	Mn	Mn	Pb, Mn	Zn
.00X	Cu, Co, V, Ti, Mg, Ca	Cu, Co, Ag, Mg, Ca	Cu, Co, Ti, Mg, Ca	Fe, Mg, Ca
.000X		Ti	Ag	Ti, Cu, Mn
Not found in the sample:	Ag, Hg, Ge, Pb, Bi	Bi, Sb, V	Bi, Sb, V	V, Cd, Co

Not found in any of above samples: Au, Pt, Pd, Ir, Hg, Mo, W, As, Tl, In, Ge, Sn, Ga, Ni, Cr, Sc, Y, Yb, La, Th, U, Nb, Ta, Zr, Be, Sr, Ba, P, B.

* Janet Fletcher, Analyst.

TABLE 4

SUPPLEMENTAL SEMI-QUANTITATIVE ANALYSES FOR MINOR ELEMENTS IN SPHALERITES OF THE COEUR D'ALENE DISTRICT*

(Only elements present in concentrations less than 1 percent are given)

Lab. No.	0.X%	.0X%	.00X%	.000X%	Not found in the sample
53–2.25SW	Cd, Pb, Mn	Ag, Cu, Ca	Hg, Ge, Sn, Co, Mg, Ga, In, Al	Ni, Ti	V, Zr, Ba, Sr
54–217SW	Cd, Pb, Mn	Cu, Ca, Ba, Mg, Al, Hg	Ag, Ga, Co	—	Ni, Ti, Zr, Ge, Sr, In
54–463SW	Cu, Cd, Mn	Pb, Mg, Ca	Hg, Ag, Ge, Co, Ga	Ti, Ba	Ni, V, Zr, Sr, In
54–464SW	Cu, Pb, Cd, Mn	Co, Mg, Ca	Hg, Ag, Ni, Ti, Ba	Ga	V, Zr, Ge, Sr, In
54–622SW	Pb, Cd, Mn, Mg	Ca, Ag	Hg, Cu, Co, Ni, Ti, Ba	Ga	V, Zr, Ge, Sr, In
54–623SW	Pb, Cd, Mn	Cu, Ti, Mg	Hg, Ag, Sn, Co, Ga, Cu	Ni	V, Zr, Ge, Sr, In, Ba
54–838SW	Cd	Hg, Cu, Ag, Pb, Mn, Mg	Ge, Co, Ga, Ti, Cu	Ni	V, Zr, In, Sr, Ba
54–839SW single crystal	Cd	Mn	Cu, Co, Ti, Mg, Ca	—	Ag, Hg, Ge, Pb, Ni, V, Zr, In, Sr, Ba
139048	Cd, Mn	Cu, Ag, Pb, Mg, Ca	Hg, In, Co, Ni, V, Ti, Zr, Ba	Sr	Ge, Ga
139049	Cd	Pb, Mn	Ag, Ge, In, V, Ti, Zr, Mg, Ca	Co, Ga	Hg, Sr, Ba
139050	Pb, Cd, Mn	—	Hg, Ag, Co, Ga, V, Ti, Zr, Mg, Ca	—	Sr, Ge, Ni, Ba, In

Not found in any of above samples: Au, Pt, Pd, Ir, Mo, W, As, Sb, Bi, Tl, Cr, Sc, Y, Yb, La, Th, U, Nb, Ta, Be, P, B.
All samples contained X% Fe.
* Janet Fletcher, Analyst.

TABLE 5

AVERAGES OF SPECTROGRAPHIC ANALYSES OF SPHALERITE FROM SEVERAL LARGE DISTRICTS

	Av. Fe (Temp. index)	Av. Cd	Av. Ga	Av. In	Av. Ge	Av. Mn	Av. Co	Number of samples
I	11.0	0.13	0.008	0.002	0.009	0.41	0.01	23
II	10.65	.14	.0038	.008	.00003	.31	.002	33
III	8.5	.17	.0045	.0047	.0049	.39	.014	78
IV	4.1	.40	.0012	.00088	.001	.27	.0055	59
V	3.76	.25	—	—	—	.75	.12	16
VI	3.60	.40	—	—	—	.41	—	38
VII	3.25	.50	—	—	—	.17	—	22
VIII	1.1	.24	.0036		.039	.017	—	31
IX	.49	.33	.0018	0	.0005	.09	0	11

I Gabrielson (6), Carbonate-Skarn group, Sweden.
II Gabrielson (6), Skellefte district, Sweden.
III All of Gabrielson's analyses.
IV Coeur d'Alene district, Idaho, this study.
V Oftedal (13), Contact deposits, Norway.
VI Oftedal, average of V and VII.
VII Oftedal (13), Urgebirge of southern Norway.
VIII Schroll (18), Vein deposits in Austria.
IX Gabrielson (6), Veins in post-Archean sedimentary rocks, Sweden.

readily recognized by color differences. The color of the single analyzed sample from the Morning 5,200 level, 2.2 percent Fe, is quite typical of sphalerite from that deep level.

CORRELATION OF FE CONTENT OF SPHALERITE WITH POSITION IN ORE SHOOT

Figure 1 shows that the Fe content of Star sphalerite does not increase with depth. In fact, the analyses indicate that sphalerite from the lower part of the mine contains less Fe, and therefore, in light of our previous discussion, formed at lower temperatures, than much sphalerite from the upper part of the ore body. Lines of equal Fe content in sphalerite in the upper and lower parts of the ore body are shown in Figure 2. The lines are, of course, diagrammatic but they do reflect real conditions.

The low formation temperatures at great depth are particularly interesting as are the suggestions of horizontal thermal gradients as shown by some near-vertical lines of equal Fe content.

An interpretation of these features might be more simple, and convincing, if there were many more times the available number of analyses. Yet, although only 40 samples from the Star mine were analyzed, the Fe content can be readily checked by the color of the sphalerite, and from the color of other samples it is apparent that trends indicated by the few samples would

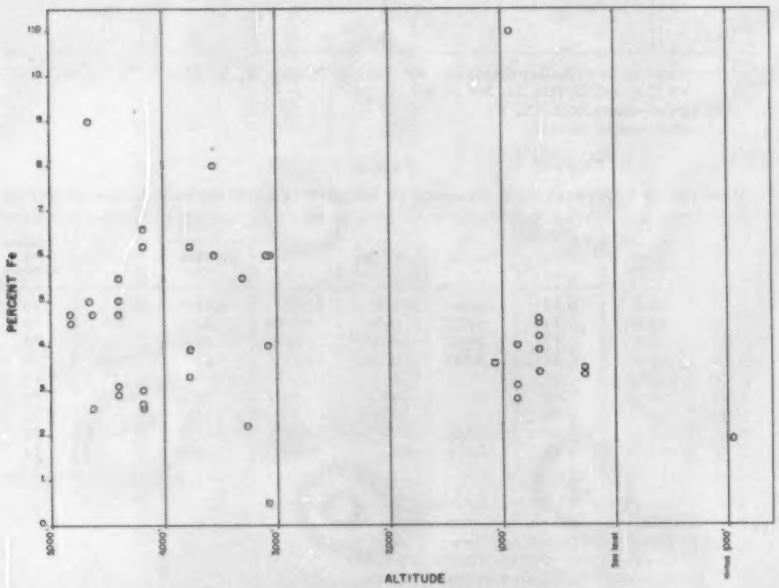


FIG. 1. Correlation of Fe content of sphalerite with altitude, Star mine, Coeur d'Alene district, Idaho.

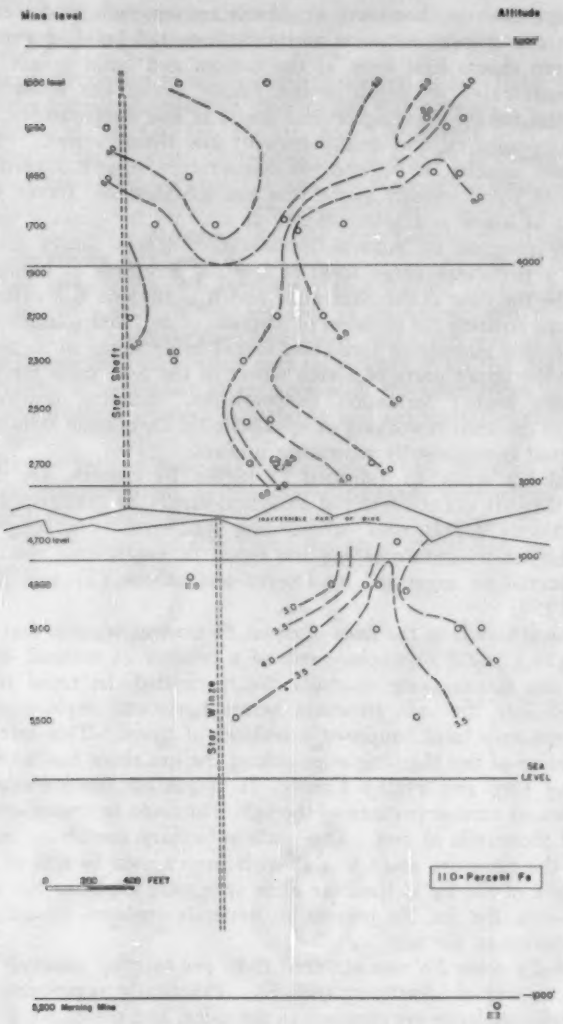


FIG. 2. Longitudinal projection of Star mine, Coeur d'Alene district, Idaho, showing generalized lines of equal Fe content, in percent, of sphalerite.

be confirmed by a greater number of analyses. The greatest value of additional quantitative values, however obtained, would be to give a closer control to lines of equal Fe content and thus bring out what appear to be finer structural features of the ore shoot.

Even more analyses, however, would not answer such fundamental questions as: do ore shoots first form at the bottom and build upward, or vice versa? If ore shoots first form at the bottom and build upward, the low relative temperatures at depth would finally prove the often suggested hypothesis that the ore-forming process starts at low temperatures, continues at higher temperatures, and finally ends at low temperatures. (For argument, we may assume the second low-temperature zone has been eroded.) One may with equal validity argue that ore solutions are forced to deposit ore minerals at lower and lower depths as avenues for passage upward are progressively plugged by mineral formation, and that finally the last ore minerals of a particular surge form at low temperatures at greatest depth. This could be the case at the Star mine and it is the one the writers prefer, although there remains the problem of disposal of depleted solutions.

Certainly, this manner of formation would bring fluids of highest energy content into the upper parts of a vein where in the Star mine the higher Fe content shows higher formation temperatures. Building downward also eliminates the constant reworking of sphalerite by Zn-bearing solutions as the sphalerite front is supposedly advancing upward.

The local hot spots, as indicated by higher Fe content, are difficult to explain but they are not the result of analytical errors, as sphalerite from these areas is distinctly darker than surrounding sphalerite. One might suggest that these higher temperatures are the result of exothermic reactions with replaced material as suggested by Dreyer and others (3) and Bailey and Cameron (1).

The vertical trends to the lines of equal Fe content suggest that ore shoot formation was a result of emplacement of a number of vertical, stringbean-like minor ore shoots along conduits that permitted the rapid rise of ore solution high into the vein structure before horizontal replacement began. Such an event may have happened a number of times. This interpretation of the formation of the Morning mine side of the ore shoot has been made by W. Manning Cox and Phillip Conley, Jr. (oral communications) on the basis of wide and narrow portions of the vein that could be traced over vertical distances of thousands of feet. One such subsidiary ore shoot on the very east end of the main ore shoot was Pb-rich from top to bottom of the mine.

The source of the Fe in the Star mine sphalerite might be the same fluid that transported the Zn, Fe present in minerals replaced by sphalerite, or some combination of the two.

Undoubtedly some Fe was acquired from pre-existing minerals but there seems to be no way of identifying such Fe. Practically mono-mineralic veinlets of Fe-rich sphalerite are common in the mine, and the entire district, and it is obvious that this Fe and Zn were introduced at the same time. Again, whether the Fe came directly with the Zn from deep sources or was picked up from earlier-formed minerals lower in the vein cannot be determined.

The writers believe that most of the Fe in sphalerite came from deep sources, but are not prepared to guess as to its method of transport, although some pyrite in the vein was probably transported as colloidal FeS_2 as shown by colloform textures that have been found in a number of places in the mine.

CORRELATION OF MINOR ELEMENTS OF SPHALERITE WITH POSITION IN ORE SHOOT AND WITH FORMATION TEMPERATURES

Graphical correlation of minor-element content of sphalerite with position in the Star ore shoot showed that distribution was random.

Correlation of Cd, Ga, Ge, Hg, In, and Co content with Fe content is also random; as an example, correlation of Cd and Fe is shown in Figure 3 (Figure 3, Correlation between Cd and Fe content of sphalerite from the Coeur d'Alene district, Idaho). Very roughly, Mn varies with Fe content, although no coefficient of correlation has been calculated. This correlation is graphically shown in Figure 4.

We have already presented evidence that the Fe content of Star mine sphalerite indicates relative temperatures of formation, and therefore, as a consequence of the relations discussed above, we are forced to conclude that there is no temperature correlation with respect to Cd, Ga, Ge, Hg, In, and Co. This conclusion is somewhat at variance with the conclusions of most other investigators of minor element occurrence and the matter is discussed in the following section.

In addition, various ratio calculations show that there is no correlation between the concentrations of the minor elements themselves. Gabrielson (6) reached this conclusion in his study of minor elements in sphalerite from Swedish deposits; he also found the same correlation we did between Mn and Fe.

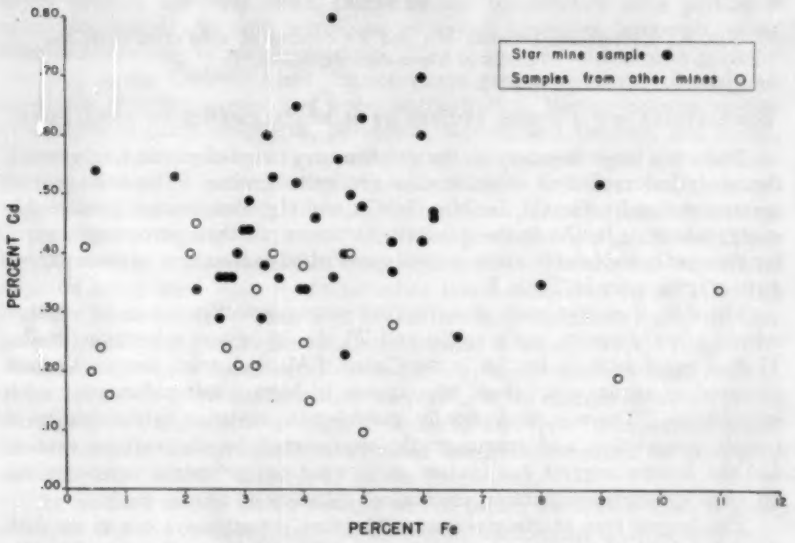


FIG. 3. Correlation between Cd and Fe content of sphalerite from the Coeur d'Alene district, Idaho.

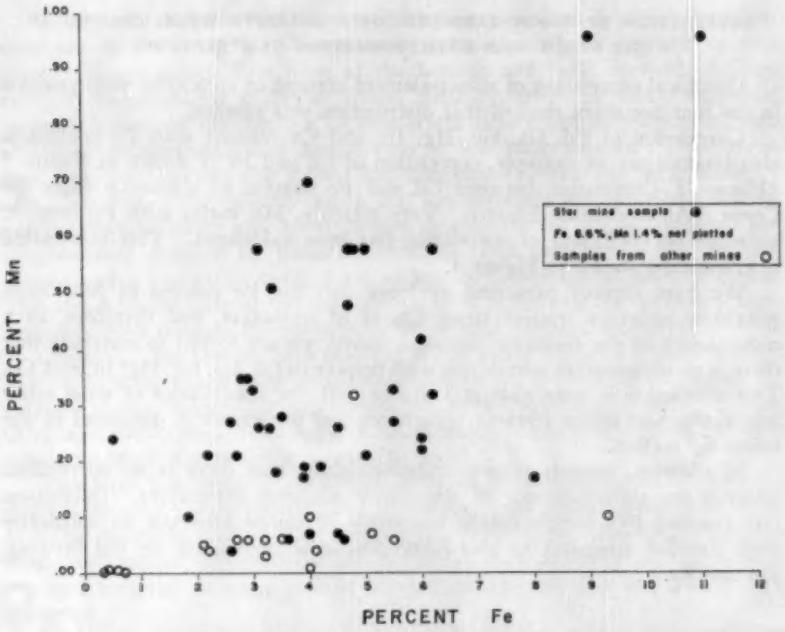


FIG. 4. Correlation between Mn and Fe content of sphalerite from the Coeur d'Alene district, Idaho.

COMPARISONS WITH OTHER STUDIES OF MINOR ELEMENTS IN SPHALERITE

There is a large literature on the geochemistry of sphalerite and, in general, the analytical results of most studies are quite similar. There is general agreement that Fe, Ge, Cd, In, Mn, Ga, Co, and Hg, elements analyzed in this study, substitute for Zn in the sphalerite structure; further, percentage ranges for these minor elements are now well established. Averages of some larger district studies are in Table 5.

There is, of course, some disagreement among investigators as to whether certain other elements, such as Sn and Tl, do or do not substitute for Zn. Tl does not substitute for Zn in the Coeur d'Alene district, but we are not prepared to argue with others who appear to have good evidence for such substitution. There is, undoubtedly, considerable variation in the quality of sample preparation and spectrography represented by the various studies, and the writers suggest due caution as to what can or cannot substitute for Zn until appropriate quantum mechanical calculations can be made.

The largest area of disagreement with other investigators has to do with the relationship between temperature and minor-element distribution. We believe that temperature has had no control on minor-element distribution in

sphalerite in the Star mine except Mn; an extrapolation of this conclusion leads us to believe that temperature has probably had little or no influence on minor-element distribution in sphalerite in other mines and districts.

It is apparent that many investigators have based their conclusions about temperatures of formation of sphalerite on the presumed high- or low-temperature nature of accompanying minerals; or the "general consensus" that a particular district or type of deposit formed at high or low temperatures. We may all agree that most sphalerite in Mississippi Valley-type deposits formed at low temperatures, but assertions about sphalerite from other types of deposits need more, and quantitative, proof.

As far as we know the absolute or relative temperature of formation of a sphalerite sample can be determined only by optical observations of bubble inclusions (controversial) and by the Fe method (a method which we are certain will become equally controversial). Optical observation of bubble inclusions is impossible for most Coeur d'Alene sphalerite because it is too fine-grained and the color is generally too dark for observation. It is also probable that known post-mineral movement in the veins has ruptured primary vacuoles. We suspect that the situation in the Coeur d'Alene district is not greatly different from the other major sphalerite districts in the world. In any event there seem to be no such studies on bubble inclusions other than those on Mississippi Valley deposits.

It is the senior writer's opinion that even if the formation temperatures of older, or younger, minerals were known, such temperatures would not necessarily indicate anything about the formation temperature of a particular sphalerite sample; in fact, actual, or presumed formation temperatures of older minerals may be very misleading. This is well demonstrated by geologic relations in the Coeur d'Alene district where gangue minerals, of analyzed sphalerite include: garnet, grunerite, anthophyllite, biotite, chlorite, pyrite (colloform in part), magnetite, pyrrhotite, siderite and ankerite, and barite. Inasmuch as the sphalerite productive stage is younger than any of these gangue minerals, it is not particularly astonishing to find that the Fe content of sphalerite has no correlation with the supposed formation temperature of the predominant gangue mineral. A broad generalization about the Coeur d'Alene district is that formation temperatures of gangue minerals of various deposits range from what might be called low hypothermal to mesothermal but that formation temperatures of productive stage sphalerite lie in the low mesothermal range; some late sphalerite formed in the epithermal range.

Realizing that in the Coeur d'Alene district gangue minerals mean nothing as far as relative sphalerite formation temperatures are concerned, we are prone to suspect the designations of "high," "medium," and "low" temperature unless the investigator has specifically determined sphalerite formation temperatures either by the "bubble" method, or by the Fe method.

As we have said in earlier sections of this paper, we believe there is good evidence that our analyzed material formed in equilibrium with Fe and that, consequently, the Fe content indicates relative temperatures of formation. We are not in a position to determine whether samples of other investigators

were or were not in equilibrium with Fe when they formed. Differing, and unknown formation pressures and possibly pH and other factors would make absolute comparisons between ore districts even more uncertain.

It seems, however, that any comparisons whatsoever of our work with past investigations, and any resulting generalizations, must depend on the Fe method for determining relative temperatures of formation. Let us then, lacking any other temperature data, assume that most of the sphalerite analyzed by other investigators formed in equilibrium with Fe, and that pH and other unknown factors must be essentially the same in order to transport and deposit zinc in any hydrothermal environment. Of necessity we will ignore the relatively minor influence of pressure. With these assumptions and qualifications in mind, let us examine some of the work done in other areas by other workers.

The district studies of Oftedal (13), Gabrielson (6), and Schroll (18) are of particular value for our purposes because Fe content was quantitatively determined for each sample (Oftedal's data are less complete). Other studies have included only a very few samples or the Fe, and other analyses, were only qualitative. Kullerud's analyses (12) are world wide and give no clear picture of a single district; the same is true of Schroll's interesting study of wurtzite, "schalenblenden," and sphalerite (17).

When Coeur d'Alene district analyses are included, the total of useful district sphalerite analyses is about 207, representing six European districts and one North American district. Table 5 presents average percentage values for these seven districts, as well as averages of all of Oftedal's (13) and Gabrielson's (6) work. There are thus nine groups tabulated according to decreasing average Fe content, and, perhaps, as to decreasing formation, temperature. Groups I, II, and III of Table 5 might be considered "high" temperature; groups IV, V, VI, and VII might be considered "medium" temperature deposits; and groups VIII and IX might be "low" temperature deposits. If Fe content represents average temperature of formation, it would appear that district data show that the influence of the formation temperature of the sphalerite on the occurrence of minor elements in sphalerite is negligible.

The tabulation seems to demonstrate that distribution of the elements involved is erratic within the earth's crust, and suggests that there are distinct minor-element provinces.

According to Evrard (5, p. 571), "The governing factor as to the presence of rare elements in sphalerite is the original composition of the parent magma. The variations resulting from modifications of temperature and pressure are then superimposed." If such is the case, comparisons between districts as was done in Table 5 would have no necessary significance, and the variations resulting from modifications of temperature and pressure would be apparent only if one considered data from a single district, or mine. Distinct trends should be apparent by plotting minor-element content against Fe content, assuming as usual that Fe was present in equilibrium concentrations. This has been done for Coeur d'Alene district sphalerite, and there is no correlation between Fe and any minor element except Mn (Fig. 4), where the correlation

is poor. The writers plotted Cd, In, and Mn against Fe for sphalerite from three Swedish districts (6); there is a correlation with Mn but none with Cd and In.

The writers have concluded that there is no evidence as to temperature influence in minor-element occurrence, other than Mn, in the Coeur d'Alene district, district-wide or in the Star ore body. The writers wonder whether any district shows such influence. Kullerud (12, p. 142) reached the same conclusion, but he would also include Mn.

FACTORS THAT DETERMINED CONCENTRATION OF MINOR ELEMENTS IN COEUR D'ALENE SPHALERITE

Available evidence indicates that equilibrium concentrations of the minor elements, except for Mn (Fe is considered a major element), were never attained in the Coeur d'Alene district; and consequently formation temperatures could not affect minor-element concentration. As shown in Table 5 usual concentrations of most of the minor elements in sphalerite are very small; it seems that equilibrium concentrations of any, other than Mn, must be exceedingly rare throughout the world.

Average concentrations of a minor element in sphalerite from any district appear to depend on the "average" amount of the element in the ore-forming solutions. Minor-element provinces are apparently real.

As an example, according to Warren and Thompson (24) the average Cd content of 122 western Canadian sphalerites was about 0.45 percent and that of ten sphalerites from the western United States and Mexico was 0.43 percent. The average of 59 Coeur d'Alene samples is 0.40 percent. It would appear that sphalerite from western North America contains about the same amount of Cd regardless of the particular ore deposit.

Lacking equilibrium concentrations the question as to why there should be variation in, for instance, Cd content in sphalerite from a single ore shoot can have no answer at present. Goldschmidt's rules were developed for situations where the ionic bond is dominant and would have no application to the covalent and metallic bonding of sulfides; Shaw (19) has shown that Goldschmidt's rules cannot be applied quantitatively to even ionic-bonded crystals. There thus seem to be no empirical rules that can be of assistance. At present, chance must be considered as determining minor-element concentration within an ore shoot.

CONCLUSIONS

1. It seems probable that the sphalerite in the Star mine formed in equilibrium with Fe; Fe contents may, therefore, be used to indicate relative temperatures of sphalerite formation in the Star mine ore body.

2. Fe contents of sphalerite indicate that the lower portions of the Star ore body formed at lower temperatures than much sphalerite from the upper portion of the ore body, corrections for pressure being considered. An interpretation is that the ore body formed from the top downward.

3. Further work with sphalerite would probably demonstrate finer struc-

tural features in the ore body, thus showing in detail how an ore shoot forms.

4. The minor elements in sphalerite, other than Mn (Fe should be considered a major element), cannot be indicators of formation temperature because equilibrium concentrations are rarely, if ever, obtained. This conclusion should have been reached on theoretical grounds before the writers started the work. The writers suspect this conclusion applies to most minerals.

5. Minor-element concentrations seem dependent on primary concentrations in ore-forming fluids. Certain portions of the earth's crust are richer in certain minor elements. The most useful approach in a search for minor elements of commercial value seems to be the identification of provinces rich in the element, and not in the examination of material from deposits supposedly formed at particular temperatures.

The writers question whether further work on minor-element distribution, in particular ore shoots, is justified. The writers believe there is a fruitful field in the investigation of major-element variation of a number of minerals in single ore shoots. It appears that such investigations will finally indicate temperatures, for particular stages, of vein and ore shoot formation. The need for laboratory investigation of binary and ternary systems involving sulfides is great. The writers might add that published quantitative analyses of sphalerite (or other minerals) from ore deposits in the United States are surprisingly few.

ACKNOWLEDGMENTS

We greatly appreciate the permission of the Sullivan Mining Company to work in the Star mine, and particularly the encouragement of R. E. Sorenson. We have greatly benefited from comments of Michael Fleischer and K. J. Murata of the U. S. Geological Survey, but responsibility for conclusions and interpretations, of course, remains with the writers.

U. S. GEOLOGICAL SURVEY,
SPOKANE, WASH., AND WASHINGTON, D. C.,
Oct. 26, 1955

REFERENCES

1. Bailey, Sturges W., and Cameron, Eugene, N., 1951, Temperatures of mineral formation in bottom run lead-zinc deposits of the Upper Mississippi Valley, as indicated by liquid inclusions: ECON. GEOL., vol. 46, p. 626–651.
2. Buerger, N. W., 1934, The unmixing of chalcopyrite from sphalerite: Amer. Mineral., vol. 19, p. 525–530.
3. Dreyer, R. M., Garrels, R. M., and Howland, A. L., 1949, Liquid inclusions in halite as a guide to geologic thermometry: Amer. Mineral., vol. 34, p. 26–34.
4. Edwards, A. B., 1947, Textures of the ore minerals: Australasian Institute of Mining and Metallurgy, 185 p.
5. Evrard, P., 1945, Minor elements in sphalerite from Belgium: ECON. GEOL., vol. 40, p. 568–574.
6. Gabrielson, O., 1945, Studier över elementfördelningen i zinkbläden fran svenska fyndorter: Sveriges Geol. Unders., Arsbok 39, no. 1, s. C., no. 468, 52 p.
7. Gavelin, S., and Gabrielson, O., 1947, Spectrochemical investigations of sulfide minerals from the ore of the Skellefte district: Sveriges Geol. Unders., Arsbok 41, no. 10, s. C., No. 491, 45 p.
8. Gordon, McKenzie, Jr., and Murata, K. J., 1952, Minor elements in Arkansas bauxite: ECON. GEOL., vol. 47, p. 169–179.

9. Graton, L. C., and Harcourt, G. A., 1935, Spectrographic evidence on origin of ores of Mississippi Valley type: Econ. Geol., vol. 30, p. 800–824.
10. Griggs, A. B., 1952, Geology and notes on ore deposits of Canyon-Nine Mile creeks area, Shoshone County, Idaho: Ph.D. thesis, Stanford University, 141 p.
11. Haberlandt, Herbert, 1953, Die systematische Grundlage und die Fortschritte in der Erforschung der Spurenelements als geochemische Leitelemente in Mineralien und Erzen: Fortschr. Miner., Bd. 31, p. 76–89.
12. Kullerud, Gunnar, 1953, The FeS–ZnS system: a geological thermometer: Norsk Geol. Tidsskrift, b. 32, h. 2–4, p. 61–147.
13. Oftedal, Ivar, 1940, Untersuchen uber die Nebenbestandteile von Erzmineralien norwegischer zinkblendefuhrender Vorkommen: Norsk Videnak. Ak., I Mat.-Naturv. Klasse Nr. 8, 103 pp.
14. Pauling, Linus, 1948, The nature of the chemical bond: 2nd Ed., Cornell University Press, 450 p.
15. Rankama, Kalervo, and Sahama, Th. G., 1950, Geochemistry: University of Chicago Press, 912 p.
16. Ransome, F. L., and Calkins, F. C., 1908, Geology and ore deposits of the Coeur d'Alene district, Idaho: U. S. Geol. Survey Prof. Paper 62.
17. Schroll, E., 1953, Uber Unterschiede im Spurengehalt bei Wurtziten, Schalenblenden un Zinkblenden: Osterr, Ak. für Wissenschaften, Mathem.-naturw. Kl., Abt. I, Bd. 162, H. 5, p. 305–332.
18. Schroll, E., 1953, Uber Minerale und Spurenelemente, Vererzung, und Enstehung der Blei-Zink-Lagerstatte Bleiberg-Kreuth, Kärntens in Osterreich: Mitteilungen der Osterreichischen Mineralogischen Gellschaft, Sonderheft, Nr. 2, p. 1–60.
19. Shaw, D. M., 1953, The camouflage principle and trace element distribution in magmatic minerals: Jour. Geol., vol. 61, p. 142–151.
20. Stoiber, R. E., 1940, Minor elements in sphalerite: Econ. Geol., vol. 35, p. 501–519.
21. Umpleby, J. B., and Jones, E. C., Jr., 1923, Geology and ore deposits of Shoshone County, Idaho: U. S. Geol. Survey Bul. 732.
22. U. S. Bureau of Mines, 1954, Minerals Yearbook 1951, U. S. Bureau of Mines.
23. Waldschmidt, W. A., 1925, Deformation in ores, Coeur d'Alene district, Idaho: Econ. Geol., vol. 20, p. 573–586.
24. Warren, H. V., and Thompson, R. M., 1945, Sphalerites from Western Canada: Econ. Geol., vol. 40, p. 309–335.

THE PARAGENESIS OF ACCESSORY MINERALS

W. W. MOORHOUSE

ABSTRACT

Most of the common non-opaque accessory minerals (apatite, zircon, sphene) may be expected to crystallize late in igneous rocks since, other things being equal, constituents in small amount in a complex solution should crystallize late. This inference is confirmed by the association of these minerals with pegmatites, the presence of apatite and sphene in certain contact metamorphic deposits, and the lack of concentrations of these minerals in the case of rocks and ores produced by crystal settling at the base of complex differentiated sills and thick flows. Texture and distribution of these accessories in igneous rocks also demonstrate their late origin.

The association of accessory minerals with biotite, hornblende, magnetite and, in some cases, quartz is demonstrated and attributed to their late magmatic crystallization. Conversely, the association of the accessory minerals with biotite in granites implies a late origin for this mineral even in acid rocks. The more nearly equal distribution of accessory minerals among the essential constituents of paragneisses as compared with igneous rocks offers a criterion for determining the origin of gneisses.

These conclusions have a bearing on the origin of late magmatic ore deposits.

INTRODUCTION

More than most sciences, the study of rocks has been burdened with an incubus of outworn ideas, some of which are merely useless baggage, and others are downright misleading. Among the latter, one which receives regular reincarnations in textbooks is the "Rosenbusch Order of Crystallization," in spite of the fact that it was superseded long ago by Bowen's Reaction Series, and Shand exposed its shortcomings in a lucid discussion of the paragenesis of igneous rocks. Also, over the same period of time, economic geologists and some petrologists interested in the relationships between rocks and ores have described cases in which oxide and sulphide ores violate this rule, e.g.: Colony (7), Mawdsley (16), Osborne (21), Fisher (10), Sampson (27), Gillson (11), Gillson, Callahan and Millar (12), Moorhouse (17, 19) Bateman (2), to mention a few. Nonetheless, it survives in many textbooks. Thus, Rankama and Sahama (25, P. 462) state, "Apatite and sphene are among the first minerals to crystallize during the formation of igneous rocks." Wahlstrom (34, p. 254) also affirms, "In general, the minor accessory minerals such as apatite, zircon, and magnetite crystallize first." More recently, Williams, Turner and Gilbert (35, p. 16) commit themselves to a similar statement, with slight qualification, "the normal order of crystallization in igneous rocks begins with the minor constituents (apatite, zircon, sphene, etc.), though some of these may also be formed at a late stage by replacement of pre-existing min-

erals." Many other examples could be quoted of the repetition of such statements in current textbooks but the above should suffice to justify the presentation of a summary of evidence that such statements are largely incorrect.

Definitions.—Before proceeding further with the discussion of this subject, it would be well to define it more precisely. Accessory minerals are defined by Holmes (15, p. 23) as "minerals occurring in small quantities in a rock, and whose presence or absence does not affect its diagnosis." Several groups of minerals are at times included in this general category. Thus plagioclase may be an accessory in a peridotite, or quartz may be an accessory in a syenite or diorite. Again, alteration products in many cases may be reckoned as accessories, where they occur in relatively small amount. These minerals are not considered in this paper. A third group is the oxides and sulphides, generally opaque, and generally present as accessories only, but locally concentrated in ores. The paragenesis of these minerals has been discussed by many writers, (such as Newhouse (20) and authors cited above), with increasing emphasis, in recent years, on their late crystallization. Finally, there are the non-opaque accessories such as zircon, apatite, sphene, monazite, rutile, xenotime, and a large number of less common minerals. These minerals occur in insignificant amounts in igneous rocks, never forming essential constituents except for a few rare cases in which they occur as ore minerals. Certain minerals belong more or less obviously to this group, but are also clearly late stage or secondary products (tourmaline, topaz, fluorite) and, since their paragenesis is not in doubt, they will not be considered further. This paper is concerned primarily with the minerals apatite, zircon and sphene, since they are relatively ubiquitous and are generally present in sufficient abundance in ordinary rocks to permit an elementary statistical treatment.

In the discussion that follows, no attempt will be made to locate the time of formation of these minerals more precisely in the paragenesis of the rock than to say that they are *not* in general the first minerals to crystallize. Thus the position taken here is not as incompatible with Buddington's (6) as he seems to imply. It is not possible to say precisely at what stage in solidification of an igneous rock these minerals have been formed. It is very likely that different minerals behave somewhat differently. One should hardly expect oxides such as chromite, magnetite and hematite, sulphides such as pyrite, phosphates such as apatite, monazite, and xenotime, and silicates such as sphene and zircon, to crystallize at the same stage of rock crystallization. The surprising feature of the accessory minerals is that most of them do appear to have remarkably close parallels in association and paragenesis (e.g. the association of apatite, zircon and magnetite). Some of these minerals undoubtedly have rather complex histories. For instance, in lava flows magnetite may occur as relatively large crystals, as fine dust scattered through the matrix, and as granular impregnations of oxidized ferromagnesian silicates. Not all these types of magnetite may have been formed simultaneously. Similarly, it is rather probable that in hydrothermally altered basic rocks, more than one generation of apatite may be present.

THEORETICAL CONSIDERATIONS

It has been pointed out by Shand (29, p. 107) that a substance in small amount in an igneous magma (such as apatite, sphene or zircon) would normally be among the last constituents to crystallize rather than one of the first. Assuming that accessory minerals are early, Vogt (31, p. 645) sought to rationalize this anomaly by supposing that accessory minerals were relatively insoluble in silicate melts compared with the more abundant constituents. He designated such minerals as "telechemic." There seems little justification for this stratagem. Prince (24) has shown that sphene behaves no differently than other silicates in silicate melts. I know of no reason why the same should not be true of zircon and more complex silicates. The work of Bredig (3) and others implies that apatite should crystallize in a normal way from complex solutions. Peach (23, p. 33) showed that phosphate in amounts equivalent to over 8 percent of apatite is retained in solution in a homogeneous glass of norite composition. The situation with respect to the oxides of iron and chromium, and the sulphides of iron, is more complicated. The work of Wager and Deer (32) and Wager and Mitchell (33) has underlined the tendency of iron to become concentrated in certain later differentiates of basic complexes, and for phosphorus and titanium to become concentrated in the middle or late middle stages of crystallization of the Skaergaard intrusion. Similar tendencies with respect to iron have been demonstrated by many investigators of igneous rock series. These trends are clearly incompatible with the early crystallization of magnetite in a differentiating magma.

GEOLOGICAL EVIDENCE

Certain characteristics of igneous rocks are incompatible with the idea of early crystallization of the accessory minerals. Perhaps the most obvious is the evidence from differentiated complexes and flows. Most of the minerals here considered have densities considerably in excess of that of the rock in which they occur, and would certainly be denser than any normal magmatic melt. If these minerals crystallized early one should expect them to form segregations at the base of differentiated complexes. This is substantially true for chromite, although even this mineral does not appear to have an early crystallization in all cases, according to Fisher (10), Sampson (27), Singewald (29a), and Bateman (2). On the other hand, magnetite, ilmenite, and, in some cases, associated apatite, invariably occur at relatively high levels in the large basic complexes. The Bushveld according to Hall (14), Bateman (2) and others, the Skaergaard intrusion (32) are notable examples, and the Sudbury norite has been shown by Collins (8) to be enriched in phosphate and titanium near its transition zone to the overlying micropegmatite. The detailed chemical investigations of Keweenawan basaltic flows by Broderick (4) confirm the evidence of these differentiated sills, by demonstrating an enrichment of the upper part of the flow in ferric iron, titania and phosphorus, among other elements. The enrichment of normative olivine and hypersthene near the base of these flows demonstrates that settling of heavy minerals has nonetheless taken place.

Closely related to examples such as the above are the features shown by ore deposits of chromite, ilmenite and magnetite. Many examples have been recorded in which ores of this type show intrusive characteristics and some of these have been summarized by Bateman (2). The restricted occurrence of these ores demonstrates their genetic relationship to the anorthosites, peridotites, and gabbros, in which they occur. The intrusive relationships which they locally present are proof of their late crystallization, and are not compatible with early crystallization of these minerals.

Accessories such as zircon, monazite, and many uranium and rare earth minerals are abundant in pegmatites and pegmatitic granites. In certain cases these minerals are best developed in the cores of such dikes, which are generally considered to have crystallized later than the borders. If such rocks are an end product of differentiation of basic magmas, as many hold, it is impossible that the accessories mentioned could be early precipitates.

Contact-metamorphic deposits provide further interesting light on this question. Apatite, for instance, is abundantly associated with metamorphic pyroxenites in the Grenville areas of Ontario and Quebec (9, 26). In these areas, it also is found in some pegmatites in considerable abundance. Sphene also occurs in abundance in pegmatites and metamorphic pyroxenites along with the apatite. Although the oxides and sulphides of iron rarely occur in abundance in pegmatites, they are very prominent in many contact-metamorphic deposits. The writer has discussed elsewhere the close relationship of contact-metamorphic and pegmatitic deposits (18). Can these minerals be produced by contact-metamorphic processes and from the same mineralizing magma be precipitated as early crystals? I doubt it.

TEXTURAL RELATIONSHIPS

The preceding discussion indicates rather conclusively that accessory minerals do not commonly crystallize early. It is worthwhile, however, to reexamine the textural evidence on which the Rosenbusch order of crystallization is based. Shand (29) has discussed certain aspects of this question fully, and I will avoid as far as possible repeating his strictures on the criteria of paragenesis that have been used. The criteria given below are quoted from his discussion (p. 107).

1. "When one crystal encloses another, the latter is of earlier formation." Shand has pointed out that this criterion is unreliable because the thin section provides a two-dimensional picture only of the fabric. This is especially true in the case of interlocking crystals, with sutured contacts, such as are characteristic of many granites, and in the case of intergrowths of many kinds. That the approach to this question is completely subjective is demonstrated by the fact that no one seriously suggests that grains of zoisite or sericite enclosed in plagioclase, or perthitic blebs of albite enveloped in microcline are therefore earlier than the enclosing crystal. We know (!) that the first are alteration products, that the second is an exsolution phenomenon; but is this a logical reason for applying a different rule to such cases, than we apply to enclosures of apatite or zircon in the major constituents of igneous rocks?

2. "The earlier crystals will generally be well shaped, the later ones less so owing to their mutual interference."

This test of paragenesis ignores completely two well-established observations. It has long been known that in metamorphic rocks, the perfection of crystal form depends upon the relative "crystallizing power" of the constituent minerals. It is a curious coincidence indeed that the accessory minerals sphene, rutile, magnetite, hematite, ilmenite are placed by Becke in the group showing the greatest tendency to euhedral development in metamorphic rocks. Thus, this one criterion is interpreted in one way in metamorphic rocks, in another way in igneous rocks.

Again, it is a familiar observation to ore geologists that many minerals (both non-metallics, such as tourmaline, epidote, biotite, carbonate, albite, and metallics, such as pyrite, magnetite, marcasite, arsenopyrite, to mention a few) have developed euhedral crystal form *by replacement* of a pre-existing rock. No one would claim that euhedral pyrite in a shale, euhedral albite in an adinole, or euhedral arsenopyrite in a greenstone schist, by virtue of their crystal form were therefore the oldest minerals in the paragenesis of the rock. They developed epigenetically, by replacing or pushing aside the original minerals. Yet in an igneous rock, the euhedral crystal is regarded as *prima facie* evidence of early crystallization. I can see no reason why one rule should apply, let us say to pyrite in a schist and another to pyrite in a granite, or why one rule should apply to tourmaline and another to apatite in the same igneous rock.

3. "When a rock contains both large and small crystals, it is to be presumed that the large crystals started to grow first." As far as the accessory minerals are concerned, this rule in fact contradicts the other two. As a generalization, it is irrelevant, as it cannot of itself be used to demonstrate a unique paragenesis. It must be fortified by other criteria, otherwise one cannot distinguish between the phenocryst and the metacryst, the porphyry and the porphyritized rock.

It is admittedly difficult to work out an unambiguous paragenesis on the basis of texture alone. In the course of the 15 years during which this problem has received my attention, many hundreds of thin sections have been examined, and a number of observations have been made, which, although individually not critical to the problem, have considerable cumulative significance:

1. In the statistical treatment, which follows, it has been found that of the common accessories, particularly apatite, zircon and sphene, about 83 percent (by volume) are located at the borders of the grains of the rock in which they occur.

2. In many cases, where the accessory minerals do occur within grains of the essential constituents, they occupy fractures, cleavage planes, or patches of alteration. Others have noted this characteristic of accessories such as zircon and apatite. Thus Anderson and Hammerand (1, p. 573 ff.) report that "Zircon, apatite, magnetite, and garnet likewise favor a distribution along grain borders, cleavages and fractures. . . . they are about the same age as late quartz."

3. Accessory minerals are erratically distributed through thin sections (Figs. 1 and 2). Commonly they occur in clusters of grains, in which the individual crystals may vary widely in their dimensions. This is more consistent with late crystallization of rather erratically distributed residual solutions than with early crystallization in a fluid uncomplicated by other solid phases. In fact the propinquity of grains of disparate sizes in a fluid magma free of other crystal would be thermodynamically improbable.

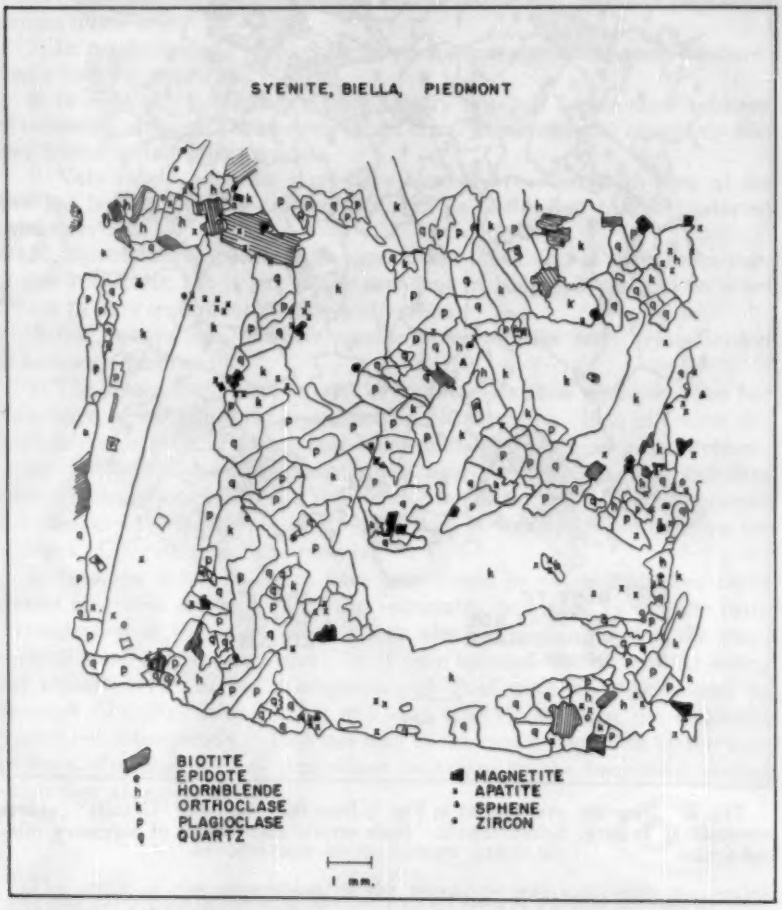


FIG. 1. "Map" of thin section of Syenite, Biella, Piedmont, based upon intersection of grain boundaries with a 1 mm grid. Note erratic distribution of accessory mineral grains.

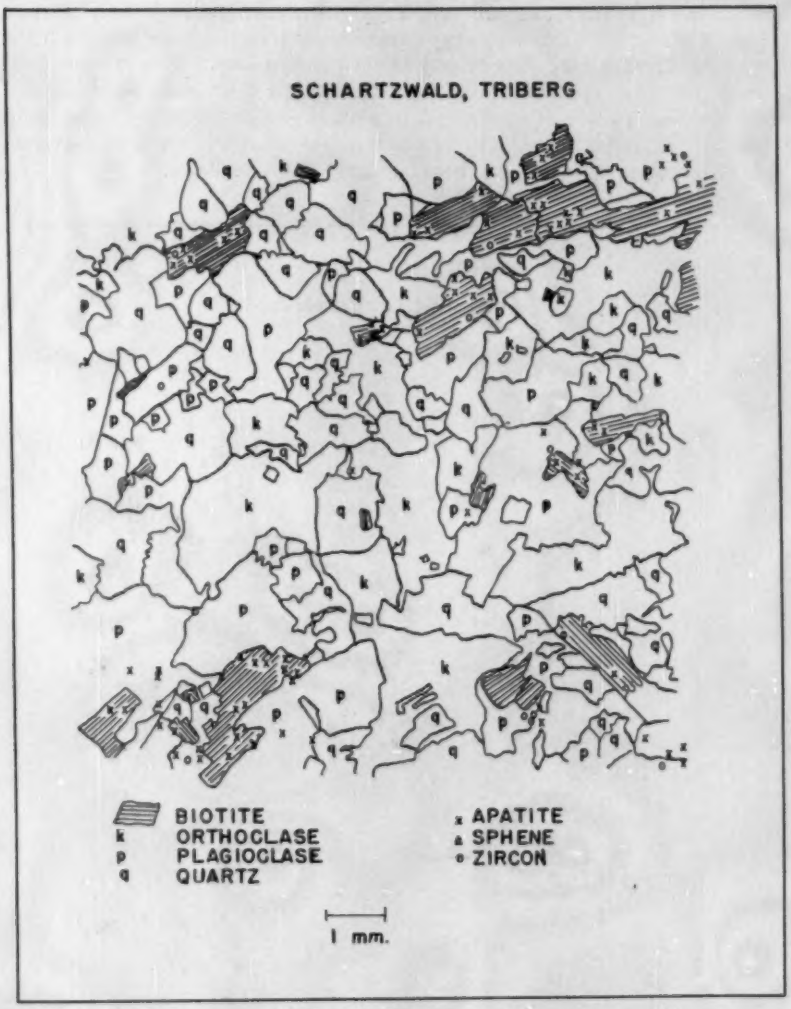


FIG. 2. Diagram, prepared as in Fig. 1, from thin section of "Granite" (quartz monzonite), Triberg, Schwartzwald. Note erratic distribution of accessory mineral grains.

4. A curious texture is sometimes observed in some granophyres and diabases. Apatite is occasionally observed in these rocks occurring in radiating tufts, whose base is the border of the host grain. The individual acicular crystals of apatite diverge inward into the grain. Such relationships agree best with development of the apatite by replacement of the enveloping mineral.

5. In many types of rocks it has been found that long crystals of apatite extend through several grains of one or more host minerals. This relationship has been considered by economic geologists to show that the penetrating mineral replaces the host mineral; it can hardly be considered a positive criterion, but the fact that these fibers rarely show dislocation or bending as they pass from one grain to the next is very suggestive of the replacement origin of the apatite.

6. In a few cases, in intermediate to acid lavas, it has been found that accessory minerals, particularly zircons, tend to be more abundant in pegmatitic streaks in the rock.

7. In porphyries and porphyritic flows, accessory minerals occur predominantly in the groundmass.

8. In most porphyritic lavas, the accessory minerals do not show evidence of corrosion, although phenocrysts of the essential constituents commonly display fretted and irregular borders.

9. Very rarely, andesitic lavas have been observed in which flow of the lava has bent and broken phenocrysts such as biotite, but has not distorted apatite crystals.

10. Apatite often appears to be more abundant in altered basic rocks than in the fresh ones. It is commonly abundant in lamprophyres that so often appear to have undergone excessive alteration.

A few observations, however, appear to support the early crystallization of accessory minerals:

1. The presence of "phenocrysts" of magnetite in some andesitic flows has been taken to indicate early crystallization of magnetite. It is of course difficult to discriminate in such a case between early crystallization and replacement. Also, as Larsen and many others have pointed out, many andesites contain abundant xenoliths and xenocrysts; the distinction between xenocryst and phenocryst is not always easy. Size alone is not a sufficient criterion for calling a magnetite grain a phenocryst.

2. In a few cases, andesites have been found in which flow lines *curve around magnetite crystals*. This can reasonably be argued to indicate early crystallization of the magnetite. It may also indicate either that the magnetite is a xenocryst (see above), or it may indicate that some other entity had separated (let us say a magnetite-rich fluid, such as is postulated by Bateman (2), Mawdsley (16, p. 46), and others), and that the magnetite crystallized subsequently. That this may be the case is suggested by the local evidence of replacement of plagioclase microlites by the magnetite, around which they appear to curve.

ASSOCIATION OF ACCESSORY MINERALS

The study of the association of the accessory minerals with the major constituents of the igneous rocks has provided some fruitful avenues of thought in connection with the general problem. Even a cursory examination of thin sections indicates a marked preference of such minerals as apatite, sphene, and

zircon for biotite, hornblende and magnetite. A very high proportion of the accessories is found either in contact with or within these minerals. If we take into account the relative abundance of these minerals, compared with quartz, feldspar, pyroxene and olivine, the association becomes even more marked.

In order to establish this preference of the accessories for certain minerals in a quantitative way, counts have been made of the number of grains of apatite, zircon, and sphene within or in contact with the major constituents of a number of rocks. The number of grains (in percent) has been divided by the percentage of the particular host mineral to give what has been termed by Peach (23) the association ratio. Since this procedure ignores the size of the accessory grains, and since, as noted above, the size varies rather much, similar ratios have been calculated for a number of rocks (for obvious reasons all plutonic) using the approximate area of the accessory grains as they appear in the thin section. These areas are determined by measuring the major and minor diameter of the crystal or grain with a micrometer eye-piece. The association ratios are calculated in the same way as for simple grain counts. Composite histograms (Figs. 3, 4) have been plotted for apatite, zircon and sphene in the case of granites, granodiorites, syenites and basic rocks.

Figure 3d shows that apatite in basic rocks has a preferential association with biotite, magnetite, and, to a less marked degree, hornblende, compared with olivine, pyroxene, and plagioclase. Since biotite and hornblende in basic rocks belong to the late magmatic or deuteric stages, apatite must crystallize in this stage rather than in the early magmatic stage of olivine, pyroxene and plagioclase.

Among the intermediate rocks, the association ratio of apatite (Fig. 3b) again shows high values for biotite, magnetite and sphene, and relatively lower values for hornblende. An interesting feature is the relatively high association with quartz which, as many writers have pointed out, crystallizes late, at least in part, in the consolidation of magmas of this composition. Similar relationships are shown by zircon (Fig. 4b) and sphene (Fig. 4d) in rocks of intermediate composition; note, however, the very high association of sphene with quartz. The marked association of apatite and sphene with one another and with magnetite emphasizes the observation already made that, however different the various accessories may be in chemical character, they display a surprising tendency to occur together.

Accessory minerals of the syenites and monzonites in general display associations very similar to those of granodiorites and their relatives (Figs. 3c, 4c, 4e). A curious exception is the high value for the association ratio of pyroxene and apatite. This is due to the inclusion in the averages of the association ratio with an alkaline pyroxene from an alkaline syenite; the value is not representative of normal syenites. The evident late crystallization of such pyroxenes in alkaline rocks is well known. The high association ratios with quartz in the case of all three accessories is due to the fact that the quartz itself is becoming an accessory mineral.

The apatite and zircon in granites (Figs. 3a, 4a) again show the charac-

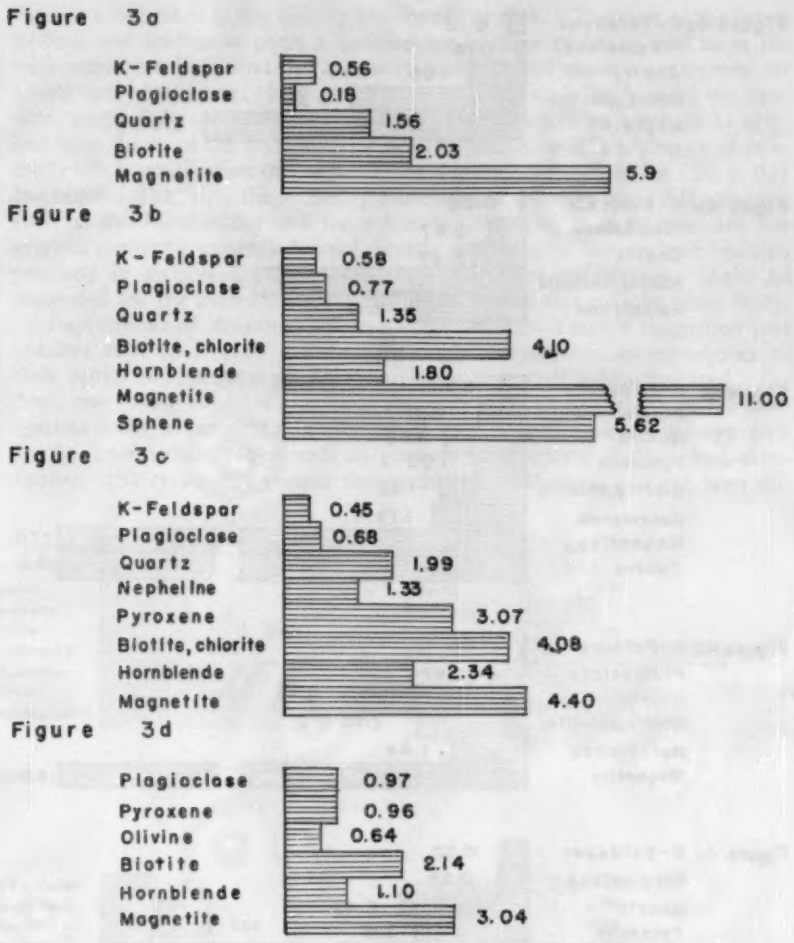


FIG. 3. Histograms of association ratios of apatite with the essential minerals of (a) granite, (b) granodiorite, (c) syenite, (d) basic rock (norite, gabbro, olivine gabbro), based on area of accessory minerals.

teristic high association with biotite and magnetite. The very low association with plagioclase is particularly notable.

The results noted above confirm those already obtained by counts of apatite grains by Moorhouse (19), Peach (23), and Buchanan (5). Figure 5 summarizes the results obtained in these investigations.

To sum up, the apatite and magnetite of the basic rocks are associated par-

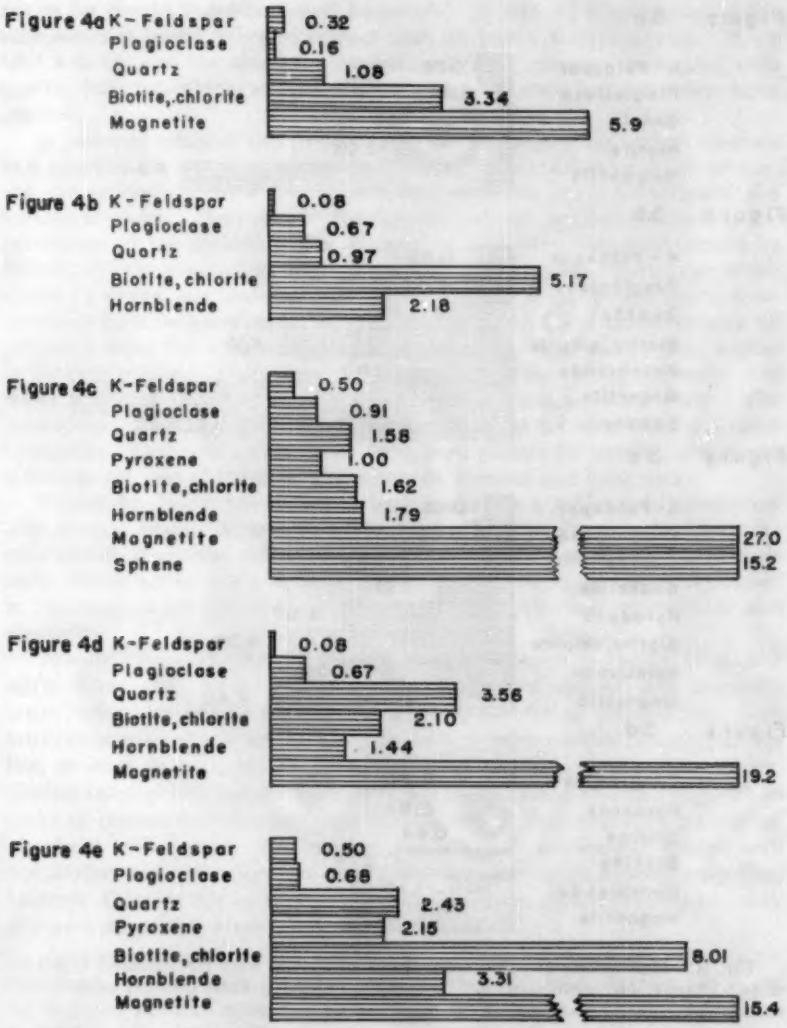


FIG. 4. Histograms of association ratios of zircon in (a) granite, (b) granodiorite, (c) syenite, and of sphene in (d) granodiorite and (e) syenite, based on area of accessory grains.

ticularly with hornblende, uralite, and biotite. These minerals belong to the late magmatic or deuteric stages of such rocks (29, p. 158) and this evidence therefore constitutes convincing proof that the accessory minerals crystal-

lized at a late stage in the cooling history of the rock. The case of the intermediate and acid rocks poses a question for in these rocks, as well as in the basic ones, one finds that the accessory minerals still show a preference for biotite and hornblende. Must we then conclude that in such rocks the apatites, magnetites, sphenes, etc., crystallized along with these minerals as original precipitates of the magma? Or are the biotites and hornblendes of relatively late crystallization themselves? In this connection Schaller (28, p. 63) has implied that ". . . the accessory minerals and other hydrous (!) minerals such as the hornblendes and the micas for example, in a granite, are not original pyrogenic minerals formed directly from magma but are later reaction products in an already formed rock. . . ." Other explanations might be suggested for the associations observed, but I think this may be most likely.

Implications of Accessory Mineral Associations.—Tuttle's suggestion that granites have undergone a rather thorough recrystallization subsequent to their initial solidification greatly complicates the relationships inferred. Indeed, one should expect a granite to resemble metamorphic rocks rather than igneous rocks, as far as the distribution of its accessory minerals is concerned. In the intermediate rocks such as granodiorites, quartz diorites and monzonites, it is reasonably certain that such recrystallization has not been all-

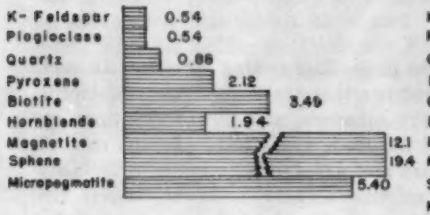


Figure 5a

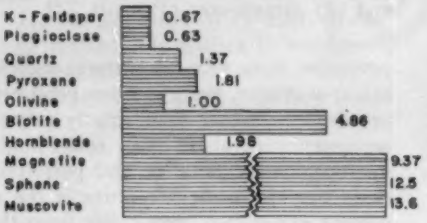


Figure 5b

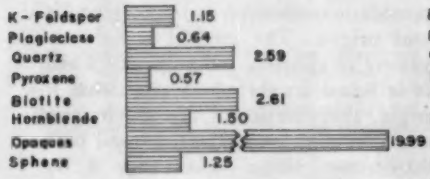


Figure 5c

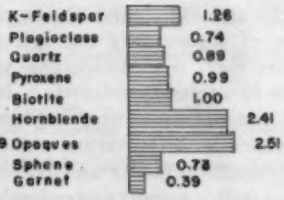


Figure 5d

FIG. 5. Histograms of association ratios of apatite (calculated from number of grains), (a) basic rocks (after Peach, 23), (b) for intermediate rocks (after Buchanan, 5), and (calculated from area of apatite grains), (c) for granite and (d) for paragneisses (after Patchett, 22).

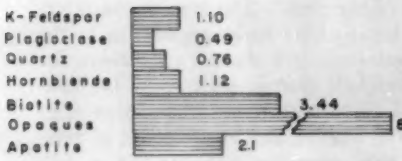


Figure 6a

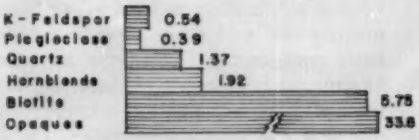


Figure 6b

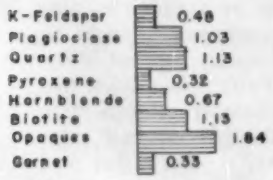


Figure 6c

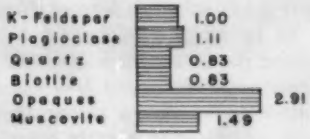


Figure 6d

FIG. 6. Histograms of association ratios of sphene (area of grains) with essential constituents of (a) granites, (b) granites, (c) paragneisses, and of zircon and (d) paragneisses (Patchett, 22).

pervasive, since primary features such as plagioclase zoning survive. In such cases, of course, there is often good evidence that the hornblende and biotite are deuteric rather than strictly primary minerals, and the observations on accessory minerals in basic rocks hold for these types also. In the case of micropegmatitic granites, and porphyries and graphic pegmatites, it is fairly clear that the present texture is the original texture, however, widely the present mineralogy may differ from the original. Until the question of the time of origin of the texture of granites is finally settled, some reservations are necessary regarding the significance of the association of accessory minerals in such rocks.

The study of accessory minerals, moreover, has been shown by the work of Rode (27) and Platchett (22) to provide a method of distinguishing between rocks of sedimentary and igneous origin. The method is only applicable where there is a considerable variety of essential minerals and a rich development of accessory minerals. It is based on the observation that in schists and gneisses of sedimentary origin, the accessories are much more evenly associated with the various minerals, in contrast to their marked preference for magnetite, biotite and hornblende in igneous rocks (Figs. 5, 6). That granites in this respect more closely resemble igneous rocks than gneisses suggests that they are produced by crystallization of magma rather than by metasomatism or other metamorphic processes.

The conclusions presented in this paper have an important bearing on the application of accessory minerals in the correlation of igneous intrusions. Groves (13) and others have used the early crystallization of the accessory

minerals as a justification for their use in this connection. Although the results of the present work do not necessarily stultify the usefulness of this technique, they do require a revision of the rationale of the method.

The writer believes that the evidence presented here points definitely to a late origin for accessory minerals. Unfortunately, the methods of investigation applied here are not conclusive. It can be said that most of the accessory minerals crystallize late, but no evidence recorded here can exclude the possibility that some such minerals are early.

It is doubtful if further petrographic work will clarify this question. It is evident that the most promising field for further research is in synthetic systems. In this way, it may be possible to determine the mechanism by which the magnetites and ilmenites of the basic complexes and the chromites of the peridotites are concentrated and crystallized. And, we may hope, at the same time we may provide a decent and long overdue burial for the perennial tradition that "accessory minerals crystallize first."

ACKNOWLEDGMENTS

This paper summarizes not only the work and experience of the writer, but also the studies of four former graduate students, Dr. P. A. Peach and Messrs. R. M. Buchanan, E. R. Rode and J. E. Patchett. The writer wishes to acknowledge his debt to these men. He has also profited by many discussions with his colleague, Professor F. G. Smith. He wishes to emphasize, however, that the conclusions presented here are his own.

Financial assistance for this research was provided by the Advisory Board on Research, University of Toronto.

UNIVERSITY OF TORONTO,
TORONTO, CANADA
Nov. 26, 1955

REFERENCES

1. Anderson, A. L., and Hammerand, V., 1940, Contact and endomorphic phenomena associated with a part of the Idaho batholith: Jour. Geol., v. 48, p. 573.
2. Bateman, A. M., 1951, The formation of late magmatic ores: ECON. GEOL., v. 46, p. 404.
3. Bredig, M. A., 1943, Phase relations in the system calcium orthosilicate-orthophosphate: Am. Mineralogist, v. 28, p. 600.
4. Broderick, T. M., 1935, Differentiation in lavas of the Michigan Keweenawan: Bull. G.S.A., v. 46, p. 503.
5. Buchanan, R. M., 1949, The paragenesis of accessory minerals in intermediate igneous rocks: M. A. Thesis (unpublished), Univ. Toronto.
6. Buddington, A. F., Fahey, J., and Vlisidis, A., 1955, Thermometric and petrogenetic significance of titaniferous magnetite: Am. Jour. Sci., v. 255, p. 497.
7. Colony, R. J., 1923, The final consolidation phenomena in the crystallization of igneous rock: Jour. Geol., v. 31, p. 169.
8. Collins, W. H., 1934, Life history of the Sudbury nickel irruptive: Trans. Royal Soc. Canada, sec. IV, v. 28, p. 160.
9. Currie, J. B., 1951, The occurrence and relationships of some mica and apatite deposits in southeastern Ontario: ECON. GEOL., v. 46, p. 765.
10. Fisher, L. W., 1929, The origin of chromite deposits: ECON. GEOL., v. 24, p. 691.
11. Gillson, J. L., 1927, Granodiorites in the Pend Oreille district of northern Idaho: Jour. Geol., v. 35, p. 1.
12. ——, 1928, Callahan, W. H., and Millar, W. B., Adirondack studies: The age of certain of the Adirondack gabbros, and the origin of the reaction rims and peculiar border phases found in them: Jour. Geol., v. 36, p. 156.

13. Groves, A. W., 1930, The heavy mineral suites and correlation of the granites of northern Brittany, the Channel Islands and the Cotentin: Geol. Mag., v. 67, p. 218.
14. Hall, A. L., 1932, The Bushveld igneous complex of the central Transvaal: S. Africa Geol. Survey Mem. 28, Pretoria.
15. Holmes, A., 1920, Nomenclature of Petrology: Murby and Van Nostrand.
16. Mawdsley, J. B., 1927, St. Urbain Area, Charlevoix District, Que.: Geol. Survey Canada, Mem. 152.
17. Moorhouse, W. W., 1938, Some titaniferous magnetites in the San Gabriel Mountains, Los Angeles Co., California: Econ. Geol., v. 33, p. 737.
18. ——, 1941, Geology of the zinc-lead deposit on Calumet Island, Que.: Geol. Soc. America, v. 52, p. 601.
19. ——, 1946, Norites and related rocks from Eagle Lake Ontario: Proc. Royal Soc. Canada, sec. IV, v. 40, p. 59.
20. Newhouse, W. N., 1936, Opaque oxides and sulphides in common igneous rocks: Bull. Geol. Soc. America, v. 47, p. 1.
21. Osborne, F. F., 1928, Certain magmatic titaniferous iron ores and their origin: Econ. Geol., v. 23, p. 724, 895.
22. Patchett, J. E., 1954, The distribution of accessory minerals as a criterion of the origin of gneisses: M.A. Thesis (unpublished), Univ. of Toronto.
23. Peach, P. A., 1947, The genetical association of accessory minerals—apatite: M.A. Thesis (unpublished), Univ. of Toronto.
24. Prince, A. T., 1943, The system albite-anorthite-sphene: Jour. Geol., v. 51, p. 1.
25. Rankama, K., and Sahama, Th. G., 1950, Geochemistry: Univ. Chicago Press.
26. Robinson, E. G., 1951, Environment and genesis of apatite and mica deposits of West Portland Township, Quebec: Ph.D. Thesis (unpublished), Univ. of Toronto.
27. Rode, E. R., 1950, Significance of accessory minerals in metamorphic rocks: M.A. Thesis (unpublished), Univ. Toronto, 1950.
28. Sampson, E., 1929, May chromite crystallize late?; Ross, C. S., Is chromite always a magmatic segregation product?; Singewald, J. T., Jr., Discussion: Econ. Geol., v. 24, p. 632.
29. Schaller, W. T., 1927, Mineral replacements in pegmatite: Am. Mineralogist, v. 12, p. 59.
30. Shand, S. J., 1947, Eruptive Rocks: Third ed., Murby.
31. Singewald, J. T., Jr., 1929, Discussion (Edward Sampson, May chromite crystallize late; C. S. Ross, Is chromite always a magmatic product?): Econ. Geol., vol. 24, p. 645.
32. Tuttle, O. F., 1952, Origin of the contrasting mineralogy of extrusive and plutonic salic rocks: Jour. Geol., v. 60, p. 107.
33. Vogt, J. H. L., 1921, The physical chemistry of the crystallization and magmatic differentiation of igneous rocks: Jour. Geol., v. 29, p. 645.
34. Wager, L. R., and Deer, W. A., 1939, The petrology of the Skaergaard intrusion, Kangerdlugssauk, east Greenland: Medd. om Grönland, 105.
35. ——, and Mitchell, R. L., 1951, The distribution of trace elements during strong fractionation of basic magma: Geo. et Cosmo, Acta, vol. 1, p. 129.
36. Wahlstrom, E. E., 1947, Igneous Minerals and Rocks: New York, Wiley.
37. Williams, H., Turner, F. J., and Gilbert, C. M., 1954, Petrography: San Francisco, Freeman.

THE ALTERATION OF ILMENITE IN BEACH SANDS

S. W. BAILEY, E. N. CAMERON, H. R. SPEDDEN,
AND RANDALL J. WEEGE

ABSTRACT

Study of the heavy mineral assemblages of beach sands from Mozambique, Ceylon, Florida, and Brazil indicates that they consist largely of ilmenite in various stages of alteration. Three successive stages of alteration are recognized, and their optical and X-ray characteristics are described. The final product of alteration is commonly finely crystalline rutile, but leucoxene composed of finely divided brookite has also been identified.

Alteration is accompanied by progressive decrease in magnetic susceptibility. The materials studied can be separated magnetically into fractions in which ilmenite grains showing various stages of alteration are concentrated differentially. The fractions therefore differ markedly in chemical composition.

INTRODUCTION

DURING February of 1954, mineralogical analysis of certain titanium-bearing beach sands was undertaken in the Laboratory of Economic Geology at the University of Wisconsin. It shortly became apparent that much of the ilmenite present in the sands is altered, and that there are corresponding variations in the TiO_2 content of the ilmenite recoverable from them. The end product of alteration is leucoxene, finely crystalline TiO_2, but the alteration process is progressive and can be divided into stages. The purpose of this paper is to describe the successive stages of alteration, to indicate their effect on the TiO_2 content of ilmenite, and to examine their influence on the susceptibility of ilmenite-bearing beach sands to magnetic concentration. The present study supplements the work recently reported by Lynd, Sigurdson, North, and Anderson (9). It confirms some of their conclusions but suggests modification of certain others.

The material studied consisted of 35 samples of heavy mineral concentrates of beach sands obtained from various localities in Portuguese East Africa (Mozambique), together with samples from beach sand deposits of Trail Ridge and Panama City, Florida; Pulmoddai, Ceylon; and the Amazon Valley, Brazil.

ACKNOWLEDGMENTS

The work on which the paper is based was done partly in the laboratories of the University of Wisconsin, partly in the Metals Research Laboratories of the Union Carbide and Carbon Corporation at Niagara Falls, N. Y. The work at Wisconsin was supported by funds furnished under the Union Carbide and Carbon Corporation Fellowship, and this support is gratefully acknowledged. The authors are likewise indebted to the Corporation for permission

to publish the results. They also wish to express their thanks to Mr. D. F. Frasché and Dr. O. N. Rove, of the Corporation, who arranged for the investigation, assisted in procuring materials, and contributed numerous valuable suggestions.

PREVIOUS WORK

The mineralogy of titanium-bearing beach sands has been in controversy for many years. Discussion centers on the nature and characteristics of the "ilmenite" extracted from them, primarily for use in pigment manufacture. There is general agreement that many of these ilmenites have TiO_2 contents that differ from the 52.7 percent of theoretical ilmenite, but there has been disagreement as to the reasons for the discrepancies.

In 1909, Palmer (12) described a mineral that he named arizonite. He concluded that the mineral had the composition $Fe_2O_3 \cdot 3TiO_2$. In 1945, Miller (10) pointed out that the ilmenites of the Florida sands were chemically similar to arizonite, but structurally different. Using X-ray techniques, he found the Florida material to be essentially amorphous, with only weak lines corresponding to those of ilmenite. He stated, however, that the so-called ilmenite of Travancore is arizonite.

In 1948, Creitz and McVay (5), using X-ray and other methods, concluded that the opaque minerals from the beach sands of Trail Ridge, Florida, are leucoxenes that vary in specific gravity and titania content. They also concluded that the most magnetic fractions have a high iron content, but that the amount of iron present is less than that contained in either arizonite or ilmenite. They suggested that the leucoxenes might be derived by weathering of ilmenite. Spencer (13) was led to the same conclusions.

In 1949, Gillson (7) stated that the mineral found on the beaches of many continental land masses had not been proved to be arizonite, but he favored the use of the name arizonite. In a later article (8), he reaffirmed this and questioned the conclusions drawn by Overholt, Vaux, and Rodda (11) that arizonite is weathered ilmenite.

Cannon (4) discussed the composition of the ilmenite of Trail Ridge in 1950 and concluded that variations in the TiO_2 content of ilmenite at this locality reflect different degrees of alteration of ilmenite to leucoxene by weathering. He stated that leucoxene is microfine, crystalline rutile.

In 1954, Lynd, Sigurdson, North, and Anderson (9) published results of a detailed study of ilmenite concentrates from certain beach sand deposits of North Carolina, Florida, Brazil, and India. This investigation is especially noteworthy because for the first time the results of chemical, X-ray, and magnetic concentration studies are correlated with study of opaque minerals of beach sands in polished surfaces. These authors concluded that the dominant heavy mineral of the concentrates studied is not arizonite but weathered ilmenite. The alteration of ilmenite is illustrated by excellent photomicrographs.

PROCEDURES FOLLOWED IN THE PRESENT INVESTIGATION

The procedures followed in the present investigation are in general the same as those followed by Lynd and his coworkers, with one principal differ-

ence. In their investigation, X-ray analysis was done only on assemblages of grains obtained by heavy mineral separation and magnetic concentration. In the present study individual grains have been investigated, first in polished surface under the microscope, then by X-ray methods. The optical characteristics of these grains can therefore be correlated directly with X-ray data. It has therefore been possible to trace directly the structural changes that take place in ilmenite with progress of alteration. On this basis, stages of alteration have been recognized.

In industry, the heavy mineral concentrate obtained from a beach sand is commonly fractionated so as to yield an ilmenite concentrate (52–65 percent TiO_2). A leucoxene concentrate (70–90 percent TiO_2) or a rutile concentrate (+ 90 percent TiO_2), or both, may also be produced. The Florida material studied by Lynd and others was an ilmenite concentrate; the nature of the other materials, whether ilmenite concentrates or total heavy mineral fractions, is not stated. In the present investigation, the material from Trail Ridge studied was an ilmenite concentrate. Each of the other samples investigated represented the total heavy mineral fraction from a beach sand sample.

THE ALTERATION OF ILMENITE AS SEEN UNDER THE MICROSCOPE

General statement.—Three stages in the alteration of ilmenite have been recognized under the microscope. They were found in all samples studied. The products of each stage have characteristic features and are readily distinguished. The stages are discussed below in order of appearance.

Stage 1 (Patchy ilmenite).—The products of the first stage of alteration are patchy intergrowths of altered and unaltered ilmenite. Successive substages in the alteration can be recognized. The first indication of alteration is the appearance of elongated stringers, rims, or rounded patches of a material having a reflectivity near that of rutile but slightly lower (Fig. 1 and 2). The color of this material is gray, in contrast to the pinkish cast of ilmenite. It is near the color of rutile but is slightly darker. As alteration progresses, the altered areas become enlarged and merge into one another. In the more advanced stages, alteration spreads until unaltered ilmenite is no longer visible, and as the grains become optically homogeneous, stage one passes into stage two. An assemblage of ilmenite grains in which various substages of alteration are represented shows a rich variety of patterns, but networks of unaltered ilmenite enclosing bulbous lenses and stringers of altered material are the most common (Fig. 3 and 4). The stringers are generally parallel to one another and evidently are developed parallel to the crystallographic basal plane of ilmenite. This arrangement is interrupted in many grains, however, along cracks, from which alteration appears to have spread laterally.

The first stage of alteration of ilmenite is accompanied by progressive decrease of anisotropism, and this can be shown quantitatively by measurement of rotation properties (2) of unaltered and altered grains. The apparent angle of rotation for unaltered ilmenite from Mozambique beach sands is 2.2

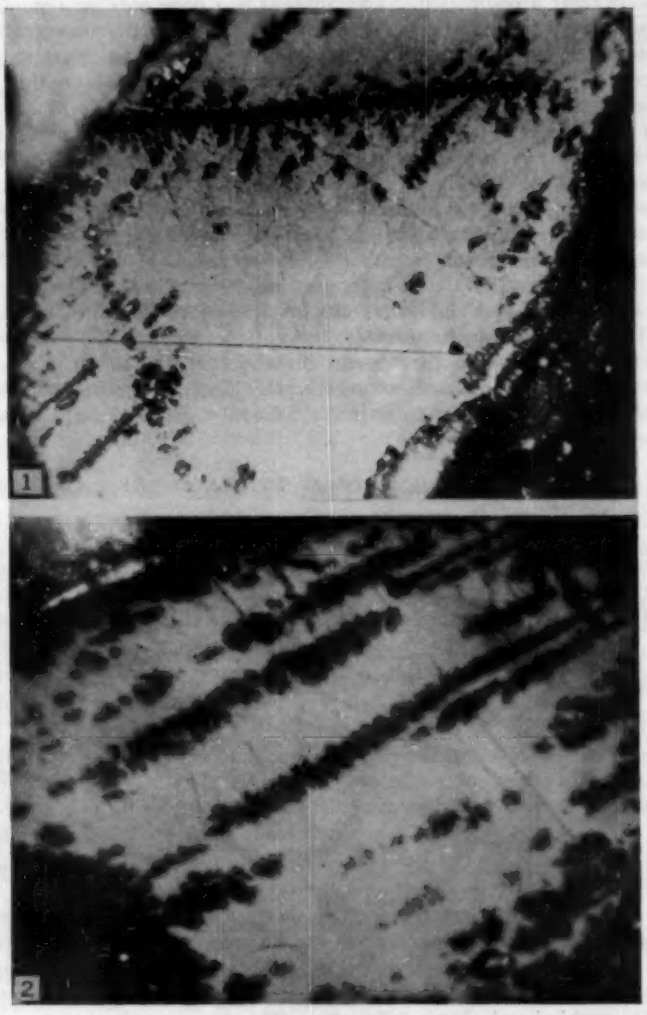


FIG. 1. Grain from beach sand, Mozambique, Africa, showing a very early phase of Stage 1. Dark—altered material, mostly amorphous iron-titanium oxide; light grey—unaltered ilmenite. Crossed nicols × 797.

FIG. 2. Grain from beach sand, Mozambique, Africa, showing a more advanced phase of Stage 1. Dark—amorphous iron-titanium oxide; grey—unaltered ilmenite. Crossed nicols × 799.

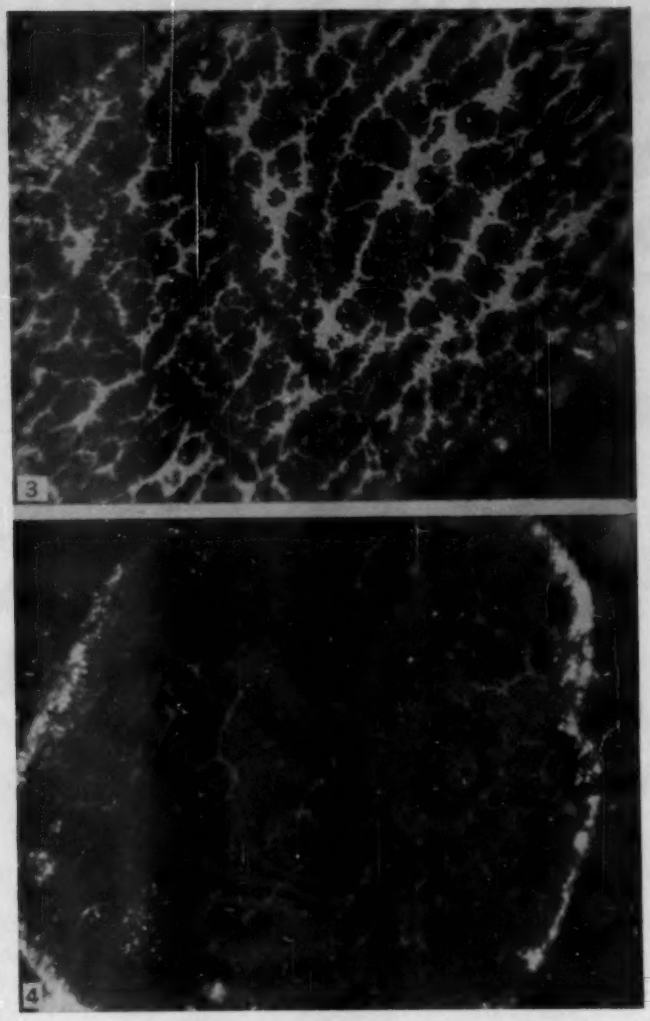


FIG. 3. Grain from beach sand, Mozambique, Africa, showing an advanced stage of patchy alteration. Note that alteration is controlled by both crystallographic planes of weakness and fractures in the grain. Dark—altered material; grey—unaltered ilmenite. Crossed nicols × 799.

FIG. 4. Grain from Mozambique, Africa, showing very late Stage 1 alteration. The grey stringers are all that remain of fresh ilmenite. The dark material is amorphous iron-titanium oxide. Note leucoxene rim (white) starting to form on the periphery of the grain. Crossed nicols × 886.

degrees in white light. The dispersion of the apparent angle of rotation is distinct, $v > r$. Altered grains give lower values of the apparent angle and show less distinct dispersion. Where altered and unaltered ilmenite are present in the same grain, the angle of apparent rotation of the altered material is always lower than that of the unaltered ilmenite. The decrease in rotation angle and dispersion appears to be progressive. For those grains in which alteration approaches stage two, dispersion is lacking and the angle of rotation becomes too small to measure.

Stage 2 (*Amorphous iron-titanium oxide*).—The end-product of stage 1 is essentially amorphous and is here designated amorphous iron-titanium oxide. The alteration has now reached stage 2. At this stage the material gives the polarization figure of an isotropic substance. All traces of the pinkish color of ilmenite have disappeared, and the reflectivity of the material is visibly higher than that of ilmenite and close to that of rutile. It is slightly greyer, however, and is opaque, showing no internal reflections. Some grains that otherwise fit the above descriptions show a weak anisotropism, but this is believed to be an indication that the alteration has not quite reached stage two.

Stage 3 (*Leucoxene*).—The final stage of alteration is marked by the development of leucoxene at the expense of amorphous iron-titanium oxide. The alteration may proceed in a variety of ways. In some grains it spreads inward from the rims (Fig. 4, 5), from cracks in the grains, or from both. In others, the development of leucoxene starts at points irregularly distributed through the grain (Fig. 6). This appears as a patchy alteration in polished surfaces. The areas formed of leucoxene are readily distinguished from amorphous iron-titanium oxide by their bright internal reflections under crossed nicols. In still other grains, leucoxene develops at innumerable points either evenly distributed within a grain or in bands (layers) parallel to the basal plane of the original ilmenite (Fig. 7). As this type of alteration progresses, the grain becomes more and more luminous under crossed nicols owing to increase in the strength of internal reflections.

In the ideal case, stage one is complete, and stage two is thereby reached, before the beginning of stage three. In many grains, however, stage three overlaps stage one, and at no time in the alteration of such grains do they consist wholly of amorphous iron-titanium oxide. The result is that many grains are composites of unaltered ilmenite, amorphous material, and leucoxene. In the materials studied, however, alteration of part of a grain to leucoxene is always preceded by alteration of that part to amorphous iron-titanium oxide. Leucoxene developed along a fracture, along the rim of a grain, or in patches in a grain is therefore always separated from fresh ilmenite by amorphous material. The relations involved are shown in Figures 5 and 6.

The leucoxene developed in the third stage of alteration is finely crystalline, and has a color in ordinary light that is close to or the same as that of rutile. Under crossed nicols, it shows mass internal reflections ranging from brown to white. It differs microscopically from ordinary rutile only in texture. Grains of ordinary rutile are either single optical units, or, if composite, con-

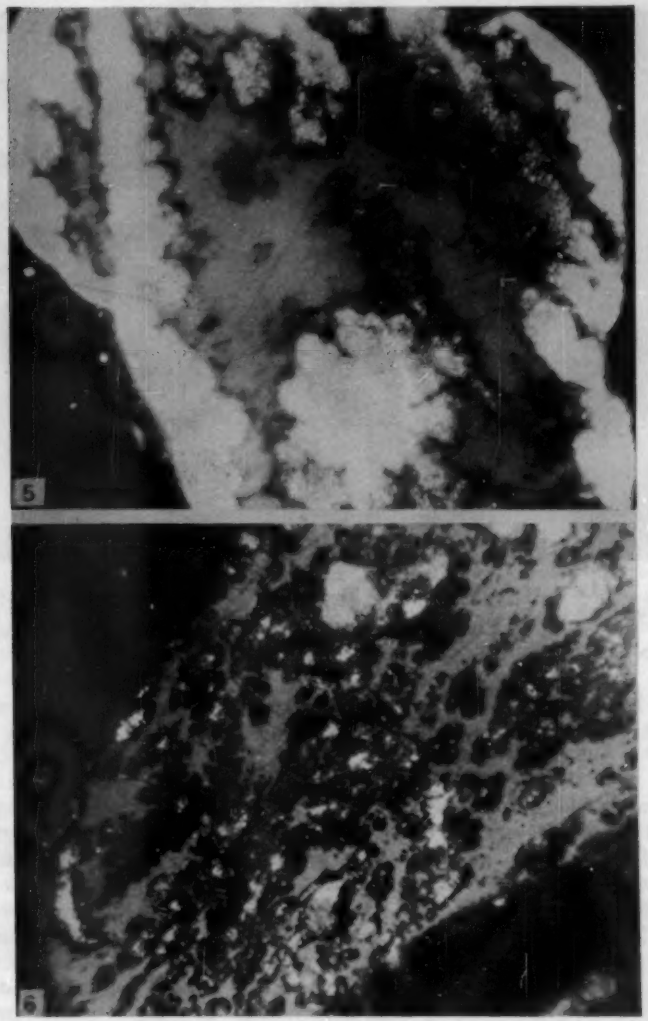


FIG. 5. Grain from beach sand, Mozambique, Africa, showing alteration rim and patches of leucoxene (white). Light grey—unaltered ilmenite; dark grey—amorphous iron-titanium oxide. Leucoxene is forming only in altered areas. Nicols × 1101.

FIG. 6. Grain from beach sand, Mozambique, Africa. All three stages are shown. The light grey is fresh ilmenite. The dark material is amorphous iron-titanium oxide. The white material is leucoxene. Note that leucoxene is forming only within areas of amorphous iron-titanium oxide. Nicols × 967.

FIG. 7. Leucoxene, Florida (Stage 3). The darker areas probably contain more iron than the white areas. Note that a parallel pattern inherited from patchy altered ilmenite is still retained. The entire grain shows internal reflections. Nicols × 1101.

sist of distinct units showing the anisotropism and twinning normal to this mineral.

CHEMICAL AND MAGNETIC DATA

Lynd and his coworkers (9) concluded that the beach sands they studied showed various degrees of alteration of ilmenite, the alteration involving leaching of TiO_2, oxidation of iron, and decrease in general magnetic susceptibility. Thus, when passed over a magnetic separator at successively higher amperages, most of the North Carolina ilmenite, the least altered material, was recovered in the low amperage range. In contrast, most of the Florida ilmenite, the most highly altered material, was recovered at the higher amperages.

The authors state that the Quilon, Brazil, and Florida concentrates studied all contain ore grains ranging from fresh ilmenite to a highly altered product approaching pure TiO_2 in composition. One would expect, therefore, that in successive magnetic fractions from one of these concentrates various products of alteration would be differentially concentrated, according to their degree of alteration and consequent decrease in magnetic susceptibility. Study of the analyses presented in the paper, however, appears to indicate that only a small degree of differential concentration was achieved. Thus successive magnetic fractions of Quilon ilmenite show a range of only 2.7 percent in TiO_2.

The first (most magnetic) fraction has a higher TiO_2 content than any of the next five fractions and, with allowance for gangue, is only 1.5 percent lower in TiO_2 than the eighth fraction. The fractions of Brazil ilmenite are difficult to evaluate, since altered magnetite is reported to be present in them. In successive magnetic fractions of Florida ilmenite, however, the variation in TiO_2 content is only about 2 percent. Values of the ratios Fe (total)/TiO_2 and Fe^{3+}/Fe (total) for successive magnetic fractions of any one beach sand likewise show a very narrow range, and the variations in ratios for successive fractions are not what one would expect if the successive fractions represent material progressively more altered by oxidation and leaching of iron. For example, for the Quilon sand, the following values are given.

WEIGHT RATIOS

Amperage	$\frac{Fe(total)}{TiO_2}$	$\frac{Fe^{3+}}{Fe(total)}$
0.5	0.43	0.68
0.75	0.45	0.66
1.00	0.46	0.62
1.25	0.49	0.53
1.50	0.47	0.54
1.75	0.44	0.66
2.00	0.42	0.76
2.25	0.40	0.82
2.50	0.39	0.86

With the above considerations in mind, the writers have devoted considerable attention to magnetic susceptibility as related to alteration. The work of Lynd and others has been carried one step farther in order to explore the relationships of chemical composition and magnetic susceptibility to the stages of alteration described in previous sections of the present paper.

Because of the small size of the heavy mineral grains in beach sands, it has not been practicable to excavate from polished surfaces pure material of each stage of alteration in amounts sufficient for chemical analysis and studies of magnetic susceptibility. Instead, the whole heavy mineral fraction of a sand has been passed over the Franz isodynamic separator and a magnetic fraction taken off at each of a series of progressively higher amperages. The resulting subfractions have then been split and one part used for chemical analysis, the other for briquetting, polishing, and mineralogical analysis by grain counts in reflected light. Chemical changes involved in alteration have then been recognized by correlating chemical and mineralogical data. The product is a statistical analysis of changes in composition and magnetic susceptibility during alteration.

Out of the thirty-nine samples studied three were selected for fractionation and mineralogical analysis. Results for the heavy mineral fraction of a fossil beach sand from the Amazon River valley, Brazil, are shown in Table I. Unaltered ilmenite, ilmenite of stage one of alteration, and ilmenite of stage two are found almost entirely in the first and most magnetic subfraction, and this indicates that no marked change in magnetic susceptibility takes place during the alteration of ilmenite to amorphous titanium-iron oxide. Composite grains consisting of ilmenite and leucoxene or ilmenite and silicates

TABLE I

MINERALOGICAL ANALYSES OF SUBFRACTIONS OBTAINED FROM THE HEAVY MINERAL CONCENTRATE FROM A SAND FROM BRAZIL

Minerals	Fraction No. 1 Magnetic at 0.25 amp		Fraction No. 2 Magnetic at 0.8 amp		Fraction No. 3 Magnetic at 1.5 amp		Fraction No. 4 Non-magnetic at 1.5 amp		Total percent. in original concent.
	% of fraction	% of original concent.	% of fraction	% of original concent.	% of fraction	% of original concent.	% of fraction	% of original concent.	
Unaltered ilmenite	5.3	4.4	1.7	0.2	1.3	tr.	0.3	tr.	4.6
Altered ilmenite of stage one	14.3	11.7	—	—	—	—	—	—	11.7
Amorphous iron-titanium oxide	25.4	20.8	6.0	0.5	—	—	—	—	21.3
Amorphous iron-titanium oxide-brown leucoxene composites	36.9	30.3	9.6	0.9	—	—	—	—	31.2
Ilmenite-silicate composites	0.2	0.2	0.3	tr.	—	—	—	—	0.2
Brown leucoxene	17.7	14.6	58.7	5.3	—	—	—	—	19.9
White leucoxene	—	—	4.5	0.4	19.6	0.5	1.9	0.1	1.0
Rutile	—	—	3.0	0.3	38.7	1.0	8.1	0.5	1.8
Rutile-silicate and leucoxene-silicate composites	—	—	0.3	tr.	2.2	tr.	0.9	0.1	0.1
Zircon	0.3	0.2	8.0	0.7	34.3	0.9	76.1	4.8	6.6
Other	—	—	8.0	0.7	3.9	0.1	12.8	0.8	1.6
Totals	100.1	82.2	100.1	9.0	100.1	2.5	100.1	6.3	100.0

likewise go into the first subfraction. Leucoxene has a variable behavior. Leucoxene showing brown internal reflections suggestive of the presence of iron oxide is more magnetic than leucoxene that shows white internal reflections. Brown leucoxene concentrates at a lower magnetic intensity than white leucoxene, which follows rutile in the fractionation process. Actually, the microscope shows that brown leucoxene is not sharply distinct from either amorphous iron-titanium oxide on the one hand or white leucoxene on the other. The alteration of the amorphous oxides to leucoxene proceeds on a minute scale. In the early stages remnants of amorphous oxides can be seen, but in the later stages they are obscured by the internal reflections of the leucoxene. The presence of residual amorphous oxides in minute particles in brown leucoxene probably explains the fact that its magnetic susceptibility, though somewhat variable, is intermediate between that of amorphous oxide and white leucoxene. No sharp line between brown and white leucoxene can be drawn, as various grains show internal reflections ranging from brown to white.

The assemblage represented in Table I has been observed in the other beach sand samples, and it would appear that separation of the heavy mineral portions of beach sands containing altered ilmenite into clean subfractions of sharply distinct mineralogical composition is not likely to be achieved by

physical means. A substantial degree of differential concentration of alteration products, however, can be achieved by appropriate magnetic treatment.

Table II gives results of mineralogical analyses of successive subfractions of the heavy mineral concentrate of beach sand from Pulmoddai, Ceylon. The results of fractionation are comparable to those shown in Table I. Here, however, two additional subfractions at 0.05 and 0.15 amperes were taken to determine whether unaltered ilmenite, altered ilmenite of stage 1, and amorphous iron-titanium oxide differ at all in magnetic susceptibility. The data indicate that there is no significant difference between unaltered ilmenite and ilmenite of stage 1, but whereas these appear in significant amounts in the 0.05, 0.15, and 0.25 subfractions, amorphous iron-titanium oxide is present in significant amounts only in the 0.15 and 0.25 subfractions. Brown leucoxene is concentrated chiefly in the 0.25 and 0.80 ampere subfractions, white leucoxene in the 0.80 ampere subfraction.

The gradational nature of the magnetic properties of the mineral assemblages in such materials is further illustrated in Table III, which gives data for three subfractions derived by treatment of a preliminary magnetic concentrate obtained from a beach sand from Mozambique. Again ilmenite of stages one and two of alteration appears largely in the first or most magnetic subfraction, but ilmenite-brown leucoxene composites are about equally divided between the first and second subfractions and brown leucoxene appears in all three, although mainly in the second and third subfractions. Samples from other localities in Mozambique gave similar results.

Table IV gives analytical data for the subfractions of Table III. If the amounts of ilmenite-leucoxene composite grains and brown leucoxene in the first subfraction are considered, it would appear that very little iron has been removed at stages one and two of the alteration of ilmenite. Iron oxide must therefore be an essential constituent of ilmenite of stage two. The analysis of subfraction 2, however, indicates that the development of leucoxene in quantity is marked by removal of much of the iron of the original ilmenite.

The data indicate that with appropriate treatment, subfractions of markedly different chemical composition can be produced magnetically from a beach sand containing ilmenite in various stages of alteration.

Further investigation of the chemistry of alteration is needed. During the present investigation an attempt has been made to correlate changes in the Fe^{3+}/Fe^{2+} ratio with stages of alteration, but the small size of the samples available has hampered the work and results have not been satisfactory. It seems evident, however, that no simple relation between stage of alteration, chemistry of alteration, and magnetic susceptibility exists. The work of Lynd et al. shows that subfractions taken at the same amperage from different beach sand concentrates do not agree in chemical composition. The chemical data for subfractions taken at 1.50 amp (Table V) illustrate this point.

Both the percentages of constituents and the Fe^{3+}/Fe^{2+} ratios differ markedly for different localities. In addition, data given in the paper indicate

TABLE II

MINERALOGICAL ANALYSES OF HEAVY MINERAL CONCENTRATE FROM BEACH SAND, PULMODDAI, CEYLON

	Magnetic at 0.05 amp		Magnetic at 0.15 amp		Magnetic at 0.25 amp		Magnetic at 0.80 amp		Magnetic at 1.5 amp		Non-magnetic at 1.5 amp		Percent of total heavy mineral concentrate
	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	
Unaltered ilmenite	25.8	2.3	17.0	7.4	9.4	2.3	—	—	—	—	—	—	12.0
Altered ilmenite (Stage 1)	60.3	5.3	53.0	23.2	35.1	8.6	0.8	tr.	—	—	—	—	37.1
Amorphous iron-titanium oxide	3.9	0.4	17.7	7.6	20.2	4.9	10.3	0.5	—	—	—	—	13.4
Ilmenite—rutile composites	—	—	0.2	0.1	0.2	0.1	0.4	tr.	—	—	—	—	0.2
Menaccanite	1.3	0.1	3.7	1.6	0.5	0.1	0.6	tr.	—	—	—	—	1.8
Composites of ilmenite, amorphous iron-titanium oxide, and leucoxene	7.2	0.6	6.1	2.7	19.4	4.7	6.1	0.3	—	—	—	—	8.3
Titaniferous magnetite	0.3	tr.	—	—	—	—	—	—	—	—	—	—	tr.
Brown leucoxene	—	—	1.5	0.6	12.4	3.0	60.8	2.8	1.1	tr.	—	—	6.4
White leucoxene	0.7	0.1	—	—	0.3	0.1	1.9	0.1	6.6	0.1	—	—	0.4
Rutile	—	—	0.2	0.1	0.3	0.1	4.6	0.2	63.7	0.8	37.6	6.6	7.8
Zircon	—	—	0.2	0.1	0.5	0.1	3.9	0.2	18.9	0.2	61.6	10.7	11.3
Heavy silicates	—	—	—	—	1.1	0.3	10.4	0.5	9.6	0.1	0.7	0.1	1.0
Hematite	—	—	—	—	—	—	—	—	—	—	0.2	tr.	tr.
Unidentified	0.4	tr.	0.4	0.2	0.3	0.1	—	—	—	—	—	—	0.3
Totals	99.9	8.8	100.0	43.6	99.7	24.4	99.8	4.6	99.9	1.2	100.1	17.4	100.0

TABLE III

MINERALOGICAL ANALYSES OF THREE MAGNETIC SUBFRACTIONS OF A BEACH SAND FROM VILLA LUISA, MOZAMBIQUE

Minerals	Fraction No. 1 Magnetic at 0.25 amp		Fraction No. 2 Magnetic at 0.8 amp		Fraction No. 3 Non-magnetic at 0.8 amp		Total percentage in original material
	% of fraction	% of original material	% of fraction	% of original material	% of fraction	% of original material	
Altered ilmenite of stage one	10.4	2.4	0.5	0.2	1.0	0.3	2.9
Amorphous iron-titanium oxide	24.2	5.7	2.8	1.2	2.0	0.6	7.5
Altered ilmenite-leucoxene composites	43.8	10.3	25.0	10.8	1.2	0.4	21.5
Brown leucoxene	5.4	1.3	22.8	9.9	12.0	4.0	15.2
White leucoxene	0.2	0.1	21.4	9.3	19.5	6.5	15.9
Altered ilmenite-silicate composites	0.2	0.1	1.0	0.4	—	—	0.5
Rutile	2.1	0.5	22.4	9.7	62.0	20.6	30.8
Rutile-silicate composites	0.2	0.1	0.4	0.2	—	—	0.3
Ilmenite-hematite intergrowths	0.3	0.1	—	—	—	—	0.1
Zircon	—	—	1.3	0.5	0.7	0.2	0.7
Other minerals	11.4	2.6	1.7	0.7	0.2	0.1	3.4
Unidentified	1.8	0.4	.7	0.3	1.4	0.5	1.2
Totals	100.0	23.6	100.0	43.2	100.0	33.2	100.0

that in a given beach sand there is no simple relation between the Fe^{3+}/total Fe ratio and magnetic susceptibility.

The magnetic susceptibility of a substance depends on the number of unpaired electrons present and the closeness of approach of such electrons in adjacent atoms. Any process affecting either of these factors may alter the magnetic susceptibility. Substitution of atoms of different size and electronic structure, for example, would affect both factors. In the case of ilmenite such a substitution might be magnesium for iron, a known substitution which has not been considered in alteration studies to date. It seems logical, also, that the presence of Fe^{3+} substituting for Fe^{2+} in the structure and oxidation, leaching, and hydration during alteration would all be effective in changing magnetic susceptibility, complicating the interpretation. At the present time, as a result, only the broader aspects of the alteration process in relation to magnetic susceptibility can be indicated.

TABLE IV

CHEMICAL ANALYSES OF THREE MAGNETIC SUBFRACTIONS OF A MOZAMBIQUE, AFRICA, BEACH SAND

	%TiO_2	%FeO*
Ilmenite, theoretical	52.66	47.34
Subfraction No. 1	56.90	28.15
Subfraction No. 2	82.1	6.9
Subfraction No. 3	95.2	0.9

* All of the iron present has been calculated as FeO.

TABLE V

CHEMICAL DATA FOR MAGNETIC SUBFRACTIONS AT 1.50 AMP, AFTER LYND ET AL. (9)

Locality	TiO_2	FeO	Fe_2O_3	Other (gangue)
North Carolina	51.3%	34.4%	8.9%	5.4%
Quilon	58.7	16.3	21.7	3.3
Brazil	55.6	13.4	24.6	6.4
Florida	63.0	5.5	26.6	4.9

X-RAY STUDIES

For identification by X-ray methods, it is customary to grind a sample to a very fine powder. This procedure has the disadvantage that certain types of information that might be given by the uncrushed single-crystal grains are necessarily lost. For this reason and in order to be able to correlate the X-ray results exactly with the optical observations, our X-ray studies were made on individual grains which had been examined previously under the reflecting microscope. Twelve grains representative of the progressive increase in alteration of ilmenite, as indicated by optical study, were selected and removed from the bakelite briquettes. The grains, measuring 0.1–0.2 mm in diameter, were mounted on the tips of fine Lindemann glass rods and X-ray diffraction photographs taken. Both powder and single-crystal camera techniques were employed. Filtered copper and iron X-radiations were used.

If the grain under study actually proves to be a single-crystal unit, its diffraction pattern will consist of a number of discrete spots. Some conclu-

TABLE VI

RESULTS OF X-RAY STUDIES OF GRAINS FROM BEACH SANDS, MOZAMBIQUE

Sample No.	Microscopic identification	X-ray identification
1	Ilmenite, unaltered	Ilmenite single-crystal. Sharp pattern.
2	Ilmenite, unaltered	Ilmenite single-crystal. Sharp pattern.
3	Early patchy altered ilmenite (stage No. 1)	Ilmenite single-crystal. Slightly diffuse spots plus powder line at d = 2.0 A.
4	Patchy altered ilmenite (stage No. 1)	Ilmenite single-crystal. Slightly diffuse spots plus powder line at d = 2.32 A.
5	Patchy altered ilmenite (stage No. 1)	Ilmenite single-crystal. Medium diffuse spots plus powder lines at d = 6.6, 3.3, 2.0 A.
6	Second stage of alteration	Ilmenite single-crystal. Few and extremely diffuse spots.
7	Ilmenite-brown leucoxene composite	Ilmenite single-crystal plus rutile (oriented aggregate) plus powder line at d = 7.3 A. Sharp ilmenite spots; rutile powder lines have intensity concentrated along certain arcs.
8	Composite of ilmenite, amorphous iron-titanium oxide, and white leucoxene	Ilmenite single-crystal plus rutile (oriented aggregate) plus powder line at d = 7.0 A. Diffuse ilmenite spots; rutile powder lines have intensity concentrated along certain arcs.
9	Brown leucoxene	Rutile (oriented aggregate) plus powder lines at d = 7.0, 2.8, 2.32 A.
10	White leucoxene	Rutile (oriented aggregate).
11	White leucoxene	Rutile (oriented aggregate).
12	White leucoxene	Brookite (oriented aggregate).

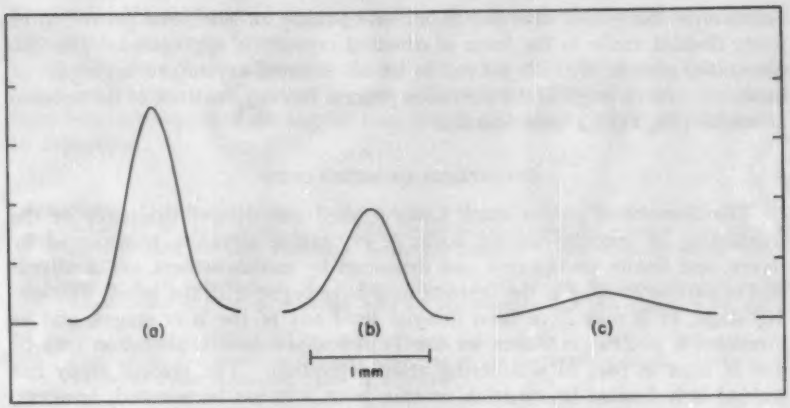


FIG. 8. Microphotometer traces through the (300) reflection of ilmenite on 15° oscillation single-crystal X-ray photographs. The peak heights are on approximately the same relative density scale, with slight variations due to differences in crystal size and exposure conditions. (a) Sample 1, unaltered ilmenite. (b) Sample 5, stage No. 1 of alteration. (c) Sample 6, stage No. 2 of alteration.

sions may then be drawn as to the degree of perfection of the crystal from a consideration of the sharpness of the spots and the presence or absence of subsidiary streaks or spots. On the other hand, if the grain is not a single unit but is an aggregate of finer particles or crystallites, the diffraction pattern will consist of a larger number of spots which will tend to coalesce into concentric circles on the film—the typical powder pattern. Some conclusions as to the size of the individual crystallites in the sample may be drawn from the degree of "spottiness" or diffuseness of the circles, and the orientation of the crystallites relative to one another may be deduced from the distribution of intensity along the circles. This type of study has enabled us to observe the progressive effect of alteration on the crystal structure of ilmenite.

Table VI lists the optical identification of the grains along with the results of the X-ray studies. It was found that there was a direct correlation between the degree of alteration of the ilmenite, as determined optically, and the progressive breakdown of the crystal lattice to an essentially amorphous state. The interruption in perfect periodicity of the ilmenite lattice is revealed on the X-ray photographs by an increasing diffuseness of the single-crystal spots. Sample No. 6 at the second stage of alteration gives only a few very diffuse spots. Most of the diffracted intensity from the sample has gone out of the spots themselves into the background, giving a pattern very close to that of the amorphous state. Microphotometer traces through the maxima of several spots are shown in Figure 8 to illustrate the increase in diffuseness and general loss of intensity as alteration proceeds. Many films showed, in addition to the single-crystal spots, one or more weak powder pattern circles. These may be due to very fine alteration products, but none could be identified

positively. All grains save one identified optically as leucoxene proved to be finely divided rutile in the form of oriented crystalline aggregates. The one exception, sample No. 12, proved to be an oriented crystalline aggregate of brookite. At no stage of the alteration process has any evidence of the mineral arizonite ($Fe_2Ti_3O_9$) been found.

CONDITIONS OF ALTERATION

The ilmenite of all the beach sands studied was derived originally by the weathering of ilmenite-bearing rocks of crystalline terranes, transported by rivers, and finally transported and deposited by marine waters. The alteration of part or even all of the ilmenite may have begun with the initial weathering stage, or it may have been delayed until any of the later stages, and as Cannon (4, p. 210) indicates for the Trail Ridge deposits, alteration may be due at least in part to weathering after deposition. The present study has yielded only limited information on this point. It has been noted, however, that in the beach sands studied, peripheral alteration of well-rounded grains is common. This alteration has evidently taken place since the rounding of the grains and must therefore have been accomplished either during the final stages of transportation and deposition or after deposition.

CONCLUSIONS

1. Ilmenite in the beach sands studied shows successive stages of alteration that can be distinguished in polished surfaces in reflected light. During the first stage ilmenite alters along fractures, grain boundaries, or internally to patchy intergrowths of ilmenite and an isotropic substance of lighter color and higher reflectivity than ilmenite. The second stage of alteration is reached when a grain has been completely transformed to the isotropic material, here designated amorphous iron-titanium oxide. The third stage involves progressive alteration of the isotropic substance to leucoxene. In many grains the first and third stages overlap, so that the grains never consist solely of amorphous iron-titanium oxide. In any given part of a grain, however, ilmenite passes into the isotropic material prior to development of leucoxene.

2. The progressive alteration is accompanied by decrease in magnetic susceptibility and increase in the ratio of TiO_2 to iron oxides. Chemical data suggest that removal of iron oxide occurs chiefly or entirely during stage 3.

3. Heavy mineral assemblages of beach sands can be divided magnetically into subfractions in which grains in various stages of alteration are concentrated differentially. The subfractions differ markedly in TiO_2 content.

4. X-ray studies indicate that the alteration of stage 1 is marked by progressive breakdown of the ilmenite lattice. At stage 2 the lattice is destroyed, and the material is essentially amorphous. This, together with optical and chemical data, suggests that the material is either an amorphous iron-titanium-oxide or a mechanical mixture of amorphous titanium oxide and iron oxide. The brown and white leucoxene of stage 3 commonly consists of oriented aggregates of finely crystalline rutile, but in some cases of finely crystalline

brookite. No evidence of the presence of the hypothetical mineral arizonite ($Fe_2Ti_3O_9$) has been found.

5. The time of the alteration of ilmenite is not entirely known, but, in the beach sands studied, alteration in part followed rounding of grains and must have been accomplished during the final stages of transportation or subsequent to deposition.

REFERENCES

1. Barksdale, J., 1949, Titanium: The Ronald Press Company, New York, p. 152–154.
2. Cameron, E. N., and Green, L. H., 1950, Polarization figures and rotation properties in reflected light and their application to the identification of ore minerals: Econ. Geol., v. 45, no. 8, p. 719–754.
3. Cameron, E. N., Hutchinson, R. W., and Green, L. H., 1953, Sources of error in the measurement of rotation properties with the ore microscope: Econ. Geol., v. 48, no. 7, p. 574–590.
4. Cannon, H. B., 1949, Economic minerals in beach sands of the southeastern United States: Proc. of the Symposium on Mineral Resources of the Southeastern U. S., University of Tennessee Press, Knoxville, Tenn., p. 202–210.
5. Creitz, E. E., and McVay, T. N., 1949, A Study of opaque minerals in Trail Ridge, Fla., dune sands: Amer. Inst. Min. Met. Eng., Trans., v. 181, p. 417–423.
6. Ford, W. E., 1926, Dana's Textbook of Mineralogy: 4th ed., John Wiley and Sons, New York.
7. Gillson, J. L., 1949, Titanium: Industrial Minerals and Rocks, 2nd ed., AIME, Ch. 49, p. 1042–1073.
8. Gillson, J. L., June 1950, Deposits of heavy minerals on the Brazilian coast: Mining Engineering 187, p. 685–693.
9. Lynd, L. E., Sigurdson, H., North, C. H., and Anderson, W. W., 1954, Characteristics of titaniferous concentrates: Mining Engineering, v. 6, no. 8, p. 817–824.
10. Miller, R., III, 1945, The heavy minerals of Florida beach and dune sands: Amer. Mineralogist, v. 30, p. 65–75.
11. Overholt, J. L., Vaux, G., and Rodda, J. L., 1950, The nature of "Arizonite": Amer. Mineralogist, v. 35, p. 117–119.
12. Palmer, Chase, 1909, Arizonite, ferric metatitanate: Amer. Jour. of Sci., ser. 4, v. 28, p. 353–356.
13. Spencer, R. V., 1948, Titanium minerals in Trail Ridge, Fla.: U. S. Bur. Mines R. I. 4208, 21 p.
14. Tyler, S. A., and Marsden, R. W., 1938, The nature of leucoxene: Jour. of Sed. Petrology, v. 8, no. 2, p. 55–58.
15. Winchell, A. N., and Winchell, H., 1951, Elements of Optical Mineralogy: 4th ed., John Wiley and Sons, New York.

SCIENTIFIC COMMUNICATIONS

THE TACONITE DEPOSITS IN THE MOUNT WRIGHT AREA OF QUEBEC[1]

The Mount Wright Area lies about 184 miles north of Sept Iles, in the Province of Quebec. The Geodetic Survey of Canada has a station named "Cold" at the north end of Quartz lake which has the following coordinates: 52° 47′ 54″ .273 North Lat., 67° 11′ 29″ .820 West Long. The elevation is 2,749 feet. The area under discussion is east of the Mount Wright block and surrounds the northern end of Quartz lake (Lac Moiree). The area lies just south of the height of land and the drainage is to the south by the Moisie river and its tributaries.

The area has been intensely glaciated and these glacial features are shown on the sheets prepared by M. C. V. Douglas and others under the general direction of Professor J. T. Wilson. The results are plotted on the National Topographical Series on the scale of 1″ = 8 miles. These sheets have been found to be of great value for they give, not only the glacial features, but also those structures, such as faults which can be seen from the air.

Geologically the rocks in this area are metamorphosed sediments intruded by gabbroic stocks. The sediments consist of alternate layers of sands and muds, which after lithification and metamorphism, are now quartzites and schists. The quartzites contain the iron minerals and grunerite and other silicates have been developed in the mudstones that are now schistose. To the southeast of Quartz lake these same sediments pass into migmatic gneisses.

The economic interest in the area is due to the occurrence of magnetite and specular hematite in the quartzites. Only to a much lesser extent are they found in the schists. Adjacent to the gabbro intrusives, specularite is more abundant than magnetite. In the field this constituted a considerable problem and one of the purposes of this paper is to seek an explanation for this relationship.

One of the fundamental tenets of geology is that the present holds the key to the past. On the beaches of Natashquan and Sept Iles magnetite sands are associated with the sands of the present shore. As it is now, so was it in Precambrian times, when the Mount Wright area formed a shore line facing in general towards the east. The sands and muds derived from the wearing down of the old continental core were deposited on an ancient shore. Grains of magnetite and possibly some other forms of iron oxides and manganese, were concentrated with the quartz grains on the strands. These minerals are therefore contemporaneous. With the consolidation of the sands and sub-

[1] Permission to publish this paper was granted by the Bellechasse Mining Corporation of Montreal and is gratefully acknowledged.

sequent metamorphism these lenses and streaks of magnetite became an integral part of the quartzites. They can thus be classed as fossil placers. Nowhere do these grains of magnetite cross from one bed to another. They occur in several beds that are at different horizons in the stratigraphical column, but never cross the beds.

A further proof of the syngenetic nature of this taconite is that the incompetent mudstone schists have not been mineralized except in a minor way. If the mineralization had been epigenetic and hypogene these incompetent beds should have been the loci for the mineralizing solutions.

It now remains to offer an explanation of the magnetite-specularite relationships. After the folding and metamorphism of the area the gabbro stocks were intruded. The specularite lies adjacent to these stocks: the magnetite lies farther away. The equations that represent this transformation might be as follows:

$$Fe_3O_4 + 6\ H_2O + \text{heat} \rightarrow 3\ Fe(OH)_3 + H_2O + H$$
$$2\ Fe(OH)_3 \rightarrow Fe_2O_3 + 3\ H_2O$$

The amount of heat required to drive the first equation from the left to the right is given as 36,000 calories per mole.

The question is whether there is enough heat in the gabbro to bring about this transformation. It is assumed that water is present in the quartzites and schists. The geological map indicates that one of the gabbro stocks measures about 800 by 800 metres in areal extent. A block of this area and an assumed depth of 400 m gives a mass of 7.7×10^{12} grams.

A mole of magnetite contains 232 grams, and requires 36,000 calories to change it to hematite according to the equation given above. If one uses the equation:

Quantity of heat = mass × specific heat × temperature

or
$$Q = m\,c\,(t_2 - t_1)$$
$$= 7.7 \times 10^{12} \times 0.2(1000 - 100)$$
$$= 13.9 \times 10^{14} \text{ calories in the gabbro.}$$

Therefore,
$$\frac{13.9 \times 10^{14}}{36 \times 10^{3}} = 0.386 \times 10^{11} \text{ moles}$$

or $0.386 \times 10^{11} \times 232$ grams

or 9 million metric tons.

This calculation can only be approximate but it gives a result that is of the order of magnitude of the hematite deposits in the vicinity of the gabbro.

The writer wishes to express his sincere thanks to all those who were with him in the field and to his colleagues Dr. N. R. Goodman, and Dr. W. R. Trost, of Dalhousie University.

DALHOUSIE UNIVERSITY,
HALIFAX, NOVA SCOTIA,
Dec. 20, 1955

GEORGE VIBERT DOUGLAS

A MODERN DEFINITION OF ORE

There is an old axiom that "the waste of today may be the ore of tomorrow." In recent years there has been increasing dissatisfaction expressed by some economic geologists with reference to the classic definition of "ore." To refresh our memories with respect to this classical understanding Bateman's (1) definition follows: "Technically it (ore) is an aggregation of ore minerals and gangue from which one or more metals may be extracted at a profit." This, and other expressions of the same sort, normally embody the three words "metals," "may," and "profit."

In the vanguard of this wave of the rebellious is professor W. R. Jones (5) who wishes to strike from our definition at least two of the key words, "metals" and "profit." His viewpoint is summarized in the reference cited as follows:

> Violent and sudden price fluctuations are alone a strong reason for omitting from the definition so constant a factor. There are other reasons.
>
> Among them is the fact that a deposit may be worked for national purposes irrespective of profit in its usual sense; that a deposit (as pointed out by the Director of the Geological Survey of Canada) may be mined "at a loss to get material that will be used to make some other undertaking profitable"; and that it is not exceptional for a mine to be operating at a loss for a period in expectation of improved markets or more efficient mining or metallurgical treatment. I would therefore suggest that those reasons, combined, offer not only strong but almost irrefutable grounds for omitting specific reference to the profit element in the definition. . . .
>
> If it can be agreed that we henceforth accept that "ore" connotes metalliferous *and* non-metalliferous deposits, and that a definition of it makes no specific reference to the profit element, we shall have got over the two chief stumbling blocks which have hitherto impeded the general acceptance of a simple definition of ore.

An opinion poll conducted by Professor Jones seemed to indicate a trend in the thinking of the profession toward an eventual exclusion from our definition of these two important elements. It is the purpose of this communication to examine the criticism and to determine if possible the extent to which revision is needed.

One of the most difficult problems in any scientific work lies in the realm of the communication of ideas. Definition is a critical factor in all communication; the ratio of signal to noise. We should note that the word ***definition*** is from a root meaning *to limit* or to be ***definite*** or specific. A symbol that is to convey meaning must have a certain amount of definition or ***limit***. That is the prime function of dictionaries and is why one would defeat the purpose of a dictionary were it to be rewritten daily and at random.

Beside the denotations or limits there is also in the meanings of words certain connotations that are the result of long usage. These meanings often embody nuances which escape delineation. On the other hand connotations of meaning change through progress, learning, and usage even to the extreme that the older definition may be violated. This is true of the ***indivisibility*** meaning of the word "atom" as well as is the claim of Jones and his followers for the word "ore."

The usefulness of words is more or less proportional to their fixed meanings. If a basic revision of meaning is indicated for "ore" then we should redefine it; otherwise, we should not tamper with the stability of our semantic symbol. Let us now consider the implications of the meanings of the two word-symbols "metals" and "profit" as they pertain to our definition of "ore" and what we consider to be its meaning.

If we are to modify our definition to include non-metalliferous deposits how far can we extend the meaning? It is now common practice to speak of both metallic and non-metallic *ore* deposits and of metallic and non-metallic *ore* minerals, but the reader will not respond favorably to the terms *oil ore, gravel ore,* and *coal ore.* It reminds one of the story of the miner's wife who, while looking at a model of a rotary oil rig, asked: "What sort of a *headframe* is that and where do the people go down?" There is obviously a limit required to the extension of the definition of "ore" into the non-metallic field.

Profit means "any advantage, benefit, or accession of good resulting from labor or exertion." It is not synonymous with money even though it is found through our economic system that the dollar is an excellent yardstick of proficiency. It is a time-honored word and can be found in the Bible; its meaning is fixed within the framework of our western culture. The thing that distinguishes an "ore" body from an uninteresting mineral association is this anticipation of *profit.*

To be entirely realistic the economic geologist would have to recognize that the nature of *profit* will vary with purpose, philosophy, and system. In the totalitarian State there is, also, the hope for *profit.* Unfortunately there is, also, in that instance a perverted sense of *good* and the *hope* is confined to the State functionary leaving little hope for the operator or the people.

In view of the definition of "profit" it seems that the classical definition of "ore" requires but little revision. If a more exacting definition is desired, the writer wishes to offer the following:

Ore: A mineral aggregate from which metallic and certain non-metallic substances could be obtained by a free operator with reasonable anticipation of profit, immediate or delayed, tangible or intangible, for himself, his company, or his country, or which could be obtained under a totalitarian government by an arbitrary State directive.

BAHNGRELL W. BROWN

MONTANA SCHOOL OF MINES,
BUTTE, MONTANA,
January 14, 1956

REFERENCES

1. Bateman, Alan M., 1950, Economic Mineral Deposits: John Wiley & Sons, N. Y., second ed., p. 22–26.
2. Carlisle, Donald, 1954, Economic aspects of the definition of ore: Bull. of the Inst. of Mining and Metallurgy (London), v. 64, no. 577 Trans., pt. 3, p. 89–99.
3. Jones, W. R., 1954a, Ore reserves; their classification and definition: Bull. of the Inst. of Mining and Metallurgy (London), v. 64, no. 577 Trans., pt. 3, p. 85–88.
4. ——, 1954b, Ore: What is it?: Bull. of the Inst. of Mining and Metallurgy (London), v. 64, no. 575 Trans., pt. 1, p. 31–34.
5. ——, 1954c, Ore: What is it?: Bull. of the Inst. of Mining and Metallurgy (London), v. 64, no. 576 Trans., pt. 2, p. 59–69.

DISCUSSION

CONCENTRATION OF URANIUM BY CARBON COMPOUNDS

Sir: Far be it from me to doubt the statement of C. F. Davidson [1] who "has made a specialized study of most of the accessible uranium deposits throughout the world." [2] He quotes from the very recent publication of Ramdohr [3] unknown to me when I wrote the discussion [4] that Davidson attacks. I have now read Ramdohr's highly detailed and objective paper and find that he has brought proof which I thought "is difficult to find in metamorphosed rocks," namely, that the "carbonaceous matter" (Davidson's thucholite) is later than the uraninite. It may be mentioned that this is almost the only thing on which the two authors agree with respect to the origin of the uranium, the hydrocarbon, and the gold. I have no intention of getting involved in a discussion of the 1600-million-years-old uraninite of the Witwatersrand but will confine myself to the much younger unmetamorphosed sediments of the Colorado Plateau and adjoining areas where I have seen many deposits in the last seven years.

First, I would like to correct an impression that Davidson might have left with the reader that most of the uranium deposits have thucholite (also called asphaltite) associated with them. There is no evidence that this substance is perhaps mysteriously hidden in the carbonaceous matter with which almost all uranium is associated in the unoxidized black ores. Here the carbonaceous matter derived from plant material was the cause of the deposition of uranium and directly or indirectly reduced the uranyl to uranous ions. This process precipitated insoluble UO_2 as uraninite or converted some to coffinite, $USiO_4 \cdot xH_2O$. It is probable that metallo-organic compounds also resulted at this time though none have been isolated in spite of the efforts of many investigators during the last six years. The lignitic ores of the Dakotas, which may contain locally 0.3 percent U_3O_8, are of a similar nature, but the mineral is either so finely divided or in the form of an organic compound that it cannot be detected except by radioactivity until the lignite weathers and yellow oxidized uranium minerals become visible.

Is there any evidence that methane gases were given off and polymerized

[1] Davidson, C. F., 1955, Concentration of uranium by carbon compounds: Econ. Geol., vol. 50, p. 879–880.

[2] Davidson, C. F., 1953, The gold uranium ores of the Witwatersrand: Mining Mag., London, vol. 88, p. 83.

[3] Ramdohr, P., 1955, Neue Beobachtugen an Erzen des Witwatersrands in Südafrika und ihre genetische Bedeutung: Abhandl. Deutsch. Akad. Wissensch., Berlin, Jahrg. 1954, no. 5, p. 26.

[4] Gruner, J. W., 1955, Concentration of uranium by carbon compounds: Econ. Geol., vol. 50, p. 542.

to thucholite according to Davidson's interpretation? The black "vitreous" lignitic layers don't appear to be any different from those of non-uraniferous lignites. It is unfortunate that he studied the Temple Mountain deposits in the San Rafael Swell in Utah more intensively than the much more common ones that contain no thucholite (ashpaltite). Since this substance is practically insoluble in the common organic solvents and is also infusible, it might be called a pyrobitumen following the classification of Abraham.[5] San Rafael Swell does contain oil seeps as mentioned by me [4] and many others as early as 1922 (Hess). Davidson asks me to "name some noteworthy occurrences of primary uranium mineralization situated within an oil and gas province where the radioactive ore is *not* accompanied by hydrocarbon." [1] On the preceding page he speaks of "woody hydrocarbon" and "thucholite hydrocarbon." The former as carbonaceous matter is present in practically all deposits. The latter of supposedly methane or similar gaseous origin is exceptional and comprises largely the "asphaltites" of the San Rafael Swell. That this is, according to Davidson, later than the uranium mineralization is merely a guess with just exactly the same relationship as that of the quartz in a vein is later than the silica-bearing solution.

Several institutions, including the U.S.G.S. Trace Elements and the Argonne National Laboratories, have spent much time investigating the Temple Mountain "asphaltites," and the weight of the evidence seems to point toward an origin and composition directly connected with wood extracts. Davidson may not have been aware of these investigations, still unfinished, when he wrote his criticism. What does he mean by an oil and gas province? If a stratigraphic column is thick enough, oil and gas may be in it somewhere. Under this definition there exist many scores of occurrences including the Lisbon Valley deposits with the famous Mi Vida Mine in southeastern Utah where no "hydrocarbon" accompanies the uranium ores. In the scores of Tertiary uranium deposits in Wyoming—and most of this state might be called an oil and gas province—we saw only one occurrence that also contained oil. No thucholite was found as far as we were able to tell.

JOHN W. GRUNER

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS 14, MINNESOTA,
February 4, 1956

COPPER DEPOSITS OF THE LAKE SUPERIOR REGION

Sir: In 1946 I and my associates (1) published a paper in this Journal bringing up to date the facts and deductions of the Calumet & Hecla geological group concerning the Keweenawan copper deposits of the Lake Superior region. This paper included a discussion of origin and reiterated a concept long recognized as fundamental by various geologists including Irving, Van Hise, Leith and Steidtman and the Calumet & Hecla group, namely, that a theory to be acceptable must explain all of the deposits of the district. These

[5] Abraham, H., 1945, Asphalts and Allied Substances: D. Van Nostrand Co., New York.

include the native copper deposits in amygdaloids, sediments, and fissures, and the associated sulphides, of which chalcocite is in great predominance, likewise in amygdaloids, sediments and fissures. In addition are the associated deposits of copper nickel and cobalt arsenides and antimonides, largely in cross fissures.

The theory of the Calumet & Hecla group, formulated in the early twenties, still seemed to be the only one that satisfactorily explained the facts.

Over a decade ago, a group from the United States Geological Survey started a study of the district and they are presenting a series of papers in which the origin of the copper deposits is treated. They do not share the belief that one mode of origin must explain all of the several types of deposit. Their papers, presented already (2), propose several modes of origin including both syngenetic and epigenetic and they have not yet treated the most important deposit thus far mined, the Calumet conglomerate, nor the mass copper, chalcocite and arsenide fissures.

I have already discussed (3) the treatment of origin as given in the Cornwall papers published in 1951. I wish to discuss the more recent U.S.G.S. papers but in order to make it more definite that the evidence thus far presented does not lead me to abandon the idea of a single origin for all the occurrences, I prefer to postpone the discussion until a larger number of their series has appeared.

Friends in teaching say they have a problem in that students show a tendency to accept the latest material published and I realize that this is only natural. As soon as the Cornwall-White paper on "Native Copper Deposits" and the Stoiber-Davidson paper on "Mineral Zoning" appear, I shall try to publish some comments promptly. My discussion even then will be handicapped because a convincing presentation includes a treatment of the Calumet conglomerate and the mass copper, arsenide and chalcocite deposits in fissures. The U. S. Geological Survey treatment of these, I understand, will not appear for some years but I do not feel that I should wait that long for at least a preliminary comment on the papers listed (2).

In the meantime, students and others are referred to our 1946 paper (1) and my 1952 discussion (3). In these papers they will find that I have anticipated and commented upon most of the arguments which are being advanced for other explanations of the origin of these deposits.

In addition to this discussion of origin which I hope to present as soon as a few more of the Survey preliminary papers appear, I hope later to review the results of their entire project in the district. A start has been made on publication of their results of underground mapping in the mines and of quadrangle folios with the usual factual matter presented in such media. A local study of details of sedimentation led them to conclusions as to the source of the materials involved which are different from those hitherto regarded as most likely from evidence obtained on both sides of the Lake Superior syncline. It is hoped that before the Survey publishes further on this subject it will send in some specialists on processes of sedimentation and on significant characteristics of lava flows to study the broader aspects of the problem not only in Michigan but all around Lake Superior since the matter

of location of the source of Keweenawan lavas and sediments is of fundamental importance. As stated by White, the determination of the source of the sedimentary material and "of the direction in which the ancient streams flowed is essential to a reconstruction of the physiography of the Keweenawan basin of deposition . . . (which) in turn may prove helpful or even necessary to the geologic search for new copper deposits" (4). Perhaps before the final publication of conclusions, the evidence afforded in the openings of the Calumet conglomerate mine will again become accessible for study.

I feel that my review of the topics of the survey other than those connected with the origin of the copper deposits had better be postponed until the final publication is out. An earlier discussion would be premature and would not be occasioned by the feeling of urgency offered by the debatable character of the topic of origin. In my final review I shall express appreciation for the completion of a long and tedious task, carried out with persistence and faithfulness and which at last provides the district with a set of useful topographic and geologic maps.

T. M. Broderick

Calumet, Michigan
December 21, 1955

REFERENCES

1. Broderick, T. M., Hohl, C. D., and Eidemiller, H. N., 1946, Recent contributions to the geology of Michigan copper district: Econ. Geol., v. 41, p. 675–725.
2. Cornwall, H. R., 1951, Ilmenite, magnetite, hematite and copper in lavas of the Keweenaw series: Econ. Geol., v. 46, p. 51–67.
——, 1951, Differentiation in lavas of the Keweenawan series and the origin of the copper deposits of Michigan: Geol. Soc. America, v. 62, p. 159–202.
——, 1951, Differentiation of magmas of the Keweenawan series: Jour. Geology, v. 59, p. 151–172.
White, Walter S., and Wright, James C., 1954, The White Pine copper deposit, Ontonagon County, Michigan: Econ. Geol., v. 49, p. 675–716.
Cornwall, H. R., and White, W. S., 1954, Native copper deposits: (not yet published) abs. Geol. Soc. America, v. 65, p. 1242–1243.
Stoiber, Richard E., and Davidson, Edward S., 1955, Mineral zoning in the Portage Lake lava series, Michigan copper district: (not yet published) abs. Am. Inst. Min. & Met. Eng. Abstracts Mining, Geology, & Geophysics Div., p. 24–25.
3. Broderick, T. M., 1952, The origin of Michigan copper deposits: Econ. Geol., v. 47, p. 215–220.
4. White, Walter S., 1952, Imbrication and initial dip in a Keweenawan conglomerate bed: Jour. Sedimentary Petrology, v. 22, p. 189–199.

Postscript to "Discussion"

Since the foregoing was submitted for publication, it has been announced that Dr. White would present a paper "The regional geologic setting of the Michigan native copper district" at an "Institute on Lake Superior Geology" to be held at Houghton, Michigan, May 11 and 12. He has very kindly sent me an outline of his paper and it presents a treatment of origin of the deposits including source of copper, source of solvent, broad structural controls and other features. Any discussion of the ideas on genesis being presented in the series of U.S.G.S. papers should certainly await the publication of this latest one by White, in addition to those by Cornwall and Stoiber referred to above.

REVIEWS

Erzlagerstätten (Ore Deposits), 3rd Edit. By HANS SCHNEIDERHÖHN. Pp. 1–375, xvi; tbls. 61. Gustav Fischer Verlag, Stuttgart, 1955.

This highly compressed revision of an earlier and well-known text represents one of the most modern treatments—if not actually the most advanced—of mineral deposits now in print, as indeed it should in view of its date. The product of a widely experienced and thoughtful investigator, it will be studied with interest by all. Despite its title, it deals at least briefly with non-metallic mineral deposits also —with sulphur, fluorspar, barite, the saline evaporites, and even coal and petroleum, though some non-metals like phosphorites are given very short shrift.

A refreshing aspect of the volume is its stress, principally in the opening pages, on the geochemical basis of ore genesis. A section is, in fact, essentially devoted to the elemental principles of geochemistry governing the mineralogy and the association of elements and of mineral deposits, in numerous brief but significant tables. This viewpoint might have been capitalized later as well; that it is not probably reflects the author's primary interest in the mineralogy, as distinct from the chemistry, of ores.

Next comes a section on fundamental processes of ore formation. Three types of isogenetic (i.e., constant or nearly constant environmentally controlled) mineral associations are recognized—the magmatic, the metamorphic, and the sedimentary. As to the second of these, the author compares metamorphosed ore deposits with anatectic or palingenetic rock types. He traces the "normal" geologic processes as related to ore deposition, suggesting in this respect the very stimulating paper by F. G. Wells and his associates on the locus of ores as presented before the Geological Society of America but published unfortunately only in abstract: downsinking geosynclines that favor sedimentary mineral deposits; deep intrusions into such sediments, giving the environment of some sulphide ores; orogenic or synorogenic plutonic magmas with typical magmatic ores (segregated, pegmatitic, contact metamorphic, and hydrothermal); later vulcanism, mainly barren or mineral deposits; the local development of resistant "kratonic" blocks and their metamorphic mineral deposits; and finally, possible deep mobilization and ore transport for longer distances—the "rejuvenated deposits," a concept which the author has applied in specific cases elsewhere. This last is stimulating, though it may lead to warm debate at least from the more rigorous magmationists, among which, in general Professor Schneiderhöhn counts himself, according to his preface.

This broadly genetic section is followed by one on more detailed classification of mineral deposits and examples, which really makes up the body of the book, except for a very brief treatment (strictly, pp. 36–42) of the application of theory to the practice of economic geology. Especially striking here is turning the clock back to Von Groddeck, whose "Typus" is the fundamental basis for classification. Mineralogy and lithologic and structural environment furnish the criteria for assigning a deposit to such a type, of which examples familiar to American geologists are "Typus Butte," "Typus Chingolobwe" (katathermal quartz-uranium veins), "Typus Leadville" (kata- to mesothermal silver-bearing lead-zinc ores), and "Typus

Mother Lode." Such an approach stresses objective similarities and may ultimately lead to a better understanding than the more theoretical one of intensity zones.

Comparing the author's approach with that of the classical and best known American texts, the condensed style and the attempts to generalize in the volume reviewed are especially striking. On the whole, the facts emphasized are mineralogic; structural control as such is little mentioned; the geochemistry of transport and deposition are not expanded; and descriptive data, such as maps, sections, and photographs of mineral relations or structures, are lacking. Thus some pragmatic reality is sacrificed to economy; but the district descriptions, however terse, are meaty and the coverage is the most cosmopolitan of any known to the reviewer.

Like most German treatises and handbooks but very few American ones, this text carries not only the usual subject index but also a comprehensive locality index —especially valuable because descriptions of certain of the many deposits cited in such books may well serve as first overviews of areas into which the reader may later plunge in more detail. In the experience of the reviewer, most "mining men" use the standard text on mineral deposits as a basic source, an encyclopedia of mining district; in fact, this may represent the chief use of such a volume for both the theoretical and the practicing economic geologist. In any case, it is an excellent reference work, broadly conceived and carried out.

CHAS. H. BEHRE, JR.

ORE GENESIS LABORATORY,
COLUMBIA UNIVERSITY,

Geology and Oil Resources of the Rose Hill District—the Fenster Area of the Cumberland Overthrust Block, Lee County, Virginia. By R. L. MILLER and J. O. FULLER. Pp. 383; pls. 50; figs. 16; tbls. 17. Virginia Geol. Survey Bull. 71, Charlottesville, 1954.

Geology and Oil Resources of the Jonesville District, Lee County, Virginia. By R. L. MILLER and W. P. BROSGÉ. Pp. 240; pls. 8; figs. 36; tbls. 3. U. S. Geol. Survey Bull. 990, Washington, 1954.

These two admirable bulletins present the full results of detailed field and subsurface studies of the classic area of shallow thrusting in the Southern Appalachians, and are valuable contributions to the mounting evidence of "thin skinned" deformation in the Appalachian Valley and Ridge Providence. (See also Rodgers, 5; Stearns, 6, 7.) These studies of the oil-producing areas associated with the Pine Mountain overthrust in southwestern Virginia and adjoining Kentucky and Tennessee, began in 1943. Publication of the Rose Hill bulletin, first completed, was delayed seven years (1947–1954) because of "printing difficulties" in the Virginia Geological Survey and appeared some months after the Jonesboro report, work for which commenced only following completion of the Rose Hill survey, in 1947. Many important conclusions from both areas have been published earlier as separate articles in scientific journals or as preliminary oil and gas maps of the U. S. Geological Survey. Both publications treat the Paleozoic stratigraphy, physiography, structure, and economic geology of these adjoining areas, and include colored geologic maps on a scale of 1/24,000, with an enlarged portion of the fenster area in the Rose Hill district on a scale of 1/12,000. Both are profusely illustrated and include representative air photographs of the region. The Virginia bulletin contains a much more comprehensive bibliography.

The requirements of detailed mapping induced the authors to pay particular attention to stratigraphic subdivision. The Paleozoic strata exposed are approximately 7,000 feet thick. Extensive descriptions of the formations and numerous

measured sections are included in both reports, totaling 170 pages in the Rose Hill bulletin and 114 pages in the Jonesville report. The problems of nomenclature of the complex Middle Ordovician succession are solved in the Jonesville report by proposing entirely new names for the units mapped, most of which coincide with units earlier recognized in the Rose Hill area, but for which a modified Butts terminology was first employed. In the Rose Hill report many Middle Ordovician formations (those above the Mascot dolomite of the Knox group and below the "Lowville" limestone) are classified as Lower Ordovician, presumably reflecting a discontinued classification of the Virginia Geological Survey which recognized a "Canadian" system and located the base of the Ordovician above the Knox group. A change to Middle Ordovician age for these units is made without comment in the Jonesville report. The Rose Hill bulletin also contains a detailed study of the Middle Ordovician bentonites, of which 13 are recognized.

Perhaps the most significant contribution of these two reports is made in the structural geology of the Pine Mountain overthrust and overlying Cumberland Mountain overthrust block. The detailed maps and study of all available well cuttings permit a refined interpretation of the structural elements and more accurate figures of the displacement on the overthrust, which have been revised downward from 7 to 5.8 miles in the Rose Hill area. The earlier interpretations of Wentworth, Butts, and Rich are corroborated and many additional complications discovered. The authors found complex fault slices along the Pine Mountain overthrust, discovered many new fensters and show most to be of a complex type, reveal crosscutting of the fault to a lower incompetent unit along strike of the block, and demonstrate folding of upper and lower blocks together, which postdates thrusting. The proof of folding after faulting (arching of the fault plane, development of the Rose Hill flexure which continues across the fault from lower to upper block, etc.) corrects Rich's idea (4, fig. 5, p. 1589–90) of regioned northward tilting of 5° set forth to explain the observed dips along the fensters. Rich's tilting concept is shown to be unternable in light of the horizontal position of the Pennsylvanian rocks in the Middlesboro "basin"; the dips are readily understood in view of the later folding. Though this aspect of Rich's analysis is corrected, the authors seem not to appreciate fully the key point made by Rich, namely that the Powell Valley "anticline" is not a typical "fold," but the result of bending of the overthrust plate at the point where the beds above the overthrust become parallel to the thrust surface in moving upward to a higher gliding level on the one side (causing SE dip in this case), and their turning back into the fault where it becomes horizontal in the higher gliding position to form the other "limb" of the structure (in this case, the NW side with NW dip). The bending is a direct result of forward movement and the stair-step arrangement of the shearing and gliding surfaces and requires no other flexure folding. The width of the "fold" thus formed was shown by Rich to be proportional to the amount of displacement on the overthrust; the "fold" is narrow and round-topped where little displacement occurs, and becomes progressively wider and flat-topped with greater displacement. Flat-bottomed "synclines" like the Middlesboro "syncline" also occur, but again not from the usual rotation of beds about an axis. The SE dip of the NW limb of this "syncline" is a result of bending of the upper plate near the place where bedding is parallel to the overthrust where the thrust shears across competent beds to seek a gliding plane parallel to bedding at a higher level. Proof of later folding diagonal to the strike of the overthrust blocks has modified the Powell Valley "anticline" as diagnosed by Rich, but has not altered the fundamental cause of its origin. The cross sections indicate the authors accept Rich's analysis, but they fail to distinguish clearly between bending simply due to forward movement and later flexure folding by defining the

Powell Valley anticline as a post-overthrust fold and indicating it "dies out" on the upper block near the boundary of the Rose Hill and Jonesville districts. This nomenclature seems unfortunate, as the displacement on the Pine Mountain overthrust exceeds 5 miles at this point, and the Powell Valley "anticline" (in the sense of Rich) is still very much "alive" and would be flat-topped here, but for the later flexure folds. If the broader usage be applied the Powell Valley "anticline" includes The Cedars syncline and adjoining Sandy Ridge and Chestnut Ridge anticlines of the Jonesville area, and the small anticline termed "Powell Valley" by the authors should be renamed.[1]

The authors discuss the major structure in three parts: stationary block, slices along the overthrust, and overthrust block.

Data on the stationary block come from the fensters and drill holes that penetrate the overthrust. The fensters are located where post-thrust folding has arched up the Pine Mountain overthrust and are in different structural positions in the two areas: In the Rose Hill area fensters occur at the upper edge of the diagonal shear where the overthrust rises from the Conasauga shale to the Upper Devonian shale, at points where beds above and below the fault are nearly parallel, but slightly upturned by later gentle folding; in the Jonesville area fensters occur at the point where the beds of the overthrust block dip back into the fault along the northwest "limb" of the false "anticline." Most of the fensters in both localities are compound, or of the "eyelid" type (2, p. 46; 3, p. 25–26), owing to the presence of slivers along the overthrust.

The slivers along the Pine Mountain overthrust are also of interest. Some in the Rose Hill area were plucked from the underlying block at points where overthrust and bedding both above and below the fault are nearly parallel. These slivers generally occur below the Pine Mountain overthrust (though separate names are given to the branch faults) and have moved differentially N28°W, 0.4 to 1.7 miles in cases where origin can be established (Rose Hill report, pl. 44, between p. 260–261). Other slivers come from the upper block. The strata of these slivers are crumpled, but bedding is generally sub-parallel to the faults above and below.

In the Jonesville area, slivers of a different type are present. The Ben Hur slice is a typical example. In it the sequence on the upper block is repeated along the northwest "limb" of the false "anticline," near the places where the beds dip toward the horizontal fault. Bedding is nearly parallel in the duplicated sequences, but the dips are steep northwest at a high angle to the main overthrust. This and similar slices occur above the Pine Mountain fault. Thus, many of the fensters in the Jonesville area are rimmed by the branch faults and the Pine Mountain overthrust passes underneath them at shallow depth. Miller (Jonesville report, p. 177) interprets the Ben Hur slice as "a large mass of rock, formerly a part of the overriding Cumberland block that has nearly, but not completely, broken loose from the block." Miller's plate 7 shows the inferred sequential stages in structural development of the area but does not include the origin of the Ben Hur slice. The Ben Hur fault is a late-stage overthrust which dips northwest over much of its extent (though it has been arched by later folding). Displacement was to the northwest, down the dip of the fault surface (where it dips NW) and occurred at a late stage in the displacement of the Pine Mountain overthrust. This caused repetition of the beds along the northwest "limb' of the Powell Valley "anticline" (sense of Rich). The Ben Hur fault dies out northeastward beyond the mapped area. Its movement was pivotal, increasing to the southwest. The Ben Hur fault is an ex-

[1] R. L. Miller indicates (in correspondence) that he prefers this alternative and that the name "Powell Valley" probably would not have been applied to the small fold in the Rose Hill district had the Jonesville district been examined first.

ception to the rule that overthrusts with less dip than bedding will shorten the section. This rule applies only when thrusting is updip; when it is downdip at a lower angle than bedding it will repeat the formations.

The Brooks well of the Rose Hill district is significant in showing that the overthrust cuts diagonally downward along strike from the Conasauga to near the base of the Rome formation just west of the Rose Hill area. The authors suggest the change in strike of the axis of the Powell Valley anticline may be related to this lower gliding surface in the Rome formation, but a similar change in strike in the Jonesville area is apparently unaccompanied by such a change in the path of the overthrust.

The beautiful maps and cross sections of both reports portray structures that may be far more common in other folded chains than is at present recognized, and the reviewer commends these publications to the attention of foreign geologists, especially, who may be unfamiliar with the concept of bedding plane thrusting as set forth by Rich, and substantiated and elaborated here.

Economic interest in the areas centers about the petroleum production, which is derived principally from the "Trenton" limestone (Middle Ordovician) of the stationary block. Production to date has come from the fenster areas of the Rose Hill district. Most producing wells occupy structurally high positions on the lower block, but some such "high" wells are dry, suggesting secondary porosity may be equally important in oil accumulation. Production is small and many wells have increased their yields after acidation. Drilling records and production statistics of all available wells are tabulated. Most wells in the Jonesville district have been abandoned before reaching the potentially productive Trenton limestone of the lower block. The authors recommend areas where further drilling might be successful.

JOHN E. SANDERS

REFERENCES CITED

1. Butts, C., 1927, Fensters in the Cumberand overthrust block in southwestern Virginia: Va. Geol. Survey Bull. 28.
2. Oriel, S. S., 1950, Geology and mineral resources of the Hot Springs window, Madison County, North Carolina: North Carolina Dept. Cons. and Devel., Min. Resources Bull. 60, p. 46.
3. ——, 1951, Structure of the Hot Springs window, Madison County, North Carolina: Am. Jour. Sci., v. 249, p. 22; 25–26.
4. Rich, J. L., 1934, Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust block, Virginia, Kentucky, and Tennessee: Am. Assoc. Petroleum Geologists Bull., v. 18, p. 1584–1596.
5. Rodgers, J., 1949, Evolution of thought on structure of Middle and Southern Appalachians: Am. Assoc. Petroleum Geologists Bull., v. 33, p. 1634–1654.
6. Stearns, R.G., 1954, The Cumberland Plateau overthrust and geology of the Crab Orchard Mountains area, Tennessee: Tenn. Div. Geol. Bull. 60, 47 p.
7. ——, 1955, Low-angle overthrusting in the central Cumberland Plateau, Tennessee: Geol. Soc. America Bull., v. 66, p. 615–628.
8. Wentworth, C. K., 1921, Russell Fork fault of southwest Virginia: Jour. Geology, v. 29, p. 351–369.

YALE UNIVERSITY,
NEW HAVEN, CONN.

La Géologie du Congo belge. By L. CAHEN. Pp. 577; pls. 36; figs. 98. H. Vaillant-Carmanne, Liège, 1954.

Mr. Cahen, who is the curator of the Royal Museum of the Belgian Congo, has contributed a long-awaited and splendid synthesis of more than 2,000 scattered publications on the geology of the Belgian Congo. At first glance, the break-

down of this large work seems to be illogical. One becomes convinced, however, by reading the first and second chapters, in spite of the very great difficulties produced by the incongruent geographic, physiographic and geologic divisions, as well as the lack of fossils in the lowest formations, that the author has surmounted these obstacles and has achieved a very clear result.

The volume is divided into four parts—General Features, The Basement (Le soubassement), The Cover (La couverture), and Mineral Resources.

The *General Features* include brief descriptions of the physiographic and geographic divisions, as well as a description of the methods used by earlier workers in attacking the different problems of correlation. The absence of fossils and the highly deformed nature of the strata demand that the succession of formations be based mainly on geometrical characteristics. In some places, intrusions and migmatization cycles are the only evidence of successive orogenic movements.

The study of the "basement" is taken up geographically by examining individual sections that are older than the pre-Middle Carboniferous. Five geographic divisions are used: Katanga, Congo oriental, Congo septentrional, Congo occidental, and the Kasai-Lomami. Each of these has a known lithologic succession but they imply nothing about the relative geochronology.

A detailed description of the stratigraphy and petrography of the region constitutes a complete and thorough analysis. More than half of the volume is devoted to the "basement," which is extremely important from an economic viewpoint, and which has been most thoroughly studied by geologists. Economic geologists have given a great deal of attention to the Katanga in particular and Mr. Cahen, in two long chapters, summarizes and coordinates all the knowledge scattered through more than 76 major publications. Many maps, photographs, structure sections, stratigraphic tables, chemical analyses, and a comprehensive bibliography accompany the study of this region.

The Cover is a detailed study of the formations younger than Middle Carboniferous. These occur in the central lower part of the country and in the regions between the surrounding ranges. The description of the cover starts with late Paleozoic glacial phenomena in the Walikale region, followed by a tentative division of the Mesozoic formations and a description of the associated basalts and kimberlites. The last named are numerous and well known in the Kundelungu, the Bushimaie, and the Kasai-Lunda. They could possibly be contemporaneous with the Cretaceous kimberlites of South Africa. Many formations, like the "Polymorphous sandstone series," the "Ocre sands series," the "Kaiso series," are, according to the author, evidences of many epeirogenic movements, climatic fluctuations, and erosion cycles.

The Pleistocene epoch is well represented in many tectonic depressions and in the fluvial terraces where fossils, artifacts, and weathering zones are seen. Three pluvial periods with their distinctive fauna can be recognized as the Kagerien, the Kamasien, and the Nakurien. Recent C^{14} datings of charcoal accompanying the artifacts seem to correlate very well with both the Cary substage and the Two Creeks horizon. The erosion cycles and the hydrographic systems are given the marked attention they deserve. The tectonic basins and the recent volcanoes are also briefly described.

The mineral resources of the Belgian Congo are far better known than their geological setting. Mr. Cahen has attempted a correlation of the scattered data obtained from mining operations with the recognized geological formations. The last two chapters are a survey of the present and potential mineral resources of the country. The Belgian Congo ranks as first producer of cobalt and uranium

in the world (excluding the U.S.S.R.), and the fifth producer of copper, in addition to significant production of Pt, Pa, Pb, Zn, Ag, Cd, and Ga. There are two distinct mineral associations in the copper deposits: the Cu–Co–U group—almost entirely restricted to the Katanga—and the Cu–Pb–Zn group having more widespread occurrence. Another less important association (Sn, Nb, Ta, W, Bi) appears in granite masses and the highly metamorphic rocks of the Kibaro-Urundi. A short survey of the potential mineral resources—oil, iron, bauxite, asbestos, barite, beryl, kyanite, diatomite, mica, precious stones, potash, sulphur and titanium —concludes the book.

This book is very well presented and is written in easily read French. We are confidant that many scientists will share our enthusiasm over this excellent publication.

JEAN BÉRARD

YALE UNIVERSITY,
NEW HAVEN, CONN.

Les Lacunes des Cristaux et leurs Inclusions Fluides. By G. DEICHA. Pp. 126; figs. 13, pls. 12 with 21 photomicrographs. Masson et Cie, Paris, 1955. Price, 950 Frs.

This monograph is dedicated to the task of bringing together and interpreting the results of observations, both of the author and of other scientists, on cavities in crystals and on their fluid contents. The rather brief chapters cover distinct aspects of the subject as follows: 1. Crystal structure and cavities formed during crystal growth. 2. Formation of contraction-bubbles in liquid-filled cavities; this includes sections on distinctions between primary and secondary inclusions and on the direct determination of the temperature at which bubbles disappear. 3. Geologic thermometry and the presence of gas under pressure; this has sections on decrepitation geothermometry and on the detection of pressurized gas inclusions by crushing in a liquid and watching to see the released bubbles. 4. Proofs of deep origin of hydrothermal and pneumatolytic solutions. 5. Vitreous and multiple-phase (gaseous and one or more liquid and/or solid) inclusions; this includes a section on pores and miarolitic cavities in volcanic rocks. 6. Conclusions.

Deicha shows that materia's to be found in cavities in crystals can be used to deduce considerable information on the history of the crystals from the moment of formation to the present. This information may include temperature and pressure of formation and analysis of fluid from which the crystal formed, and in some cases the maximum or minimum temperature to which the crystal may have been subjected after formation. The fact that fluid inclusions persist unchanged over long periods of geologic time suggests that diffusion through crystals is negligible under at least some geologically important conditions, a remark of interest to students of metamorphism and other kinds of rock transformation. This book is provided with a good table of contents (37 items), lists of illustrations, and an index of more than 200 entries, making its information easily accessible. The summary bibliography (133 titles) is a convenient source for general and classic references; more than 60 additional references of less general interest are cited in footnotes throughout the book. This is a valuable book on a timely and fascinating subject, well worth the time required for a careful perusal; I hope it will become a widely known reference work for future generations of students and researchers.

HORACE WINCHELL

Water, The Yearbook of Agriculture 1955. Pp. 752; illus. U. S. Dept. of Agriculture, Washington, D. C., 1955. Price, $2.00.

The Secretary of Agriculture states in a foreword that "water has become one of our major national concerns." This Yearbook is meant to supply as much practical information as the Department can provide about water for those who use it, and to explain the nature, behavior and conservation of water in agriculture.

The book consists of 98 separate articles by a slightly larger number of contributors, arranged under the editorship of Alfred Stefferud. It is arranged in 13 sections, e.g., need for water; where we get water; water and soil; caring for watersheds; water and forests, crops, irrigation, ranges and pastures, and wildlife; gardens, turf, and orchards; drainage of fields; pure water for farms and cities; and a look to the futue. These section headings give an idea of the content of the book. It also touches upon hydroelectric power, and industrial use and pollution, but the main theme is water in its relation to agriculture. There is also a chapter presenting both sides, without comment, of the ancient debate on water dowsing.

The book is comprehensive and authoritative, and is written in a non-technical style. It is a valuable book for farmers, country gardeners, homeowners and industrial users of water, and should prove a handy reference book for all who are interested in water.

Stratigraphic Geology. By MAURICE GIGNOUX. 4th Edition in French (1950). Translated into English by Gwendolyn G. Woodford. Pp. 698; figs. 155. W. H. Freeman & Co., San Francisco, 1955. Price, $9.50.

The earlier editions of this book have become well known throughout the world since the appearance of the first edition in 1925. This fourth edition brings stratigraphic knowledge up to date of 1949. After an introductory chapter dealing with the Materials of Stratigraphy, the following ten chapters consider the Precambrian (incidentally, the spelling given here is followed) through to the Quaternary. The later knowledge of the stratigraphy of the Alps has been incorporated and perhaps the greatest additions have been to the discussions of the Tertiary; notably that of North Africa.

The translator has done an excellent job in rendering difficult French into smoothly reading English. This translation unquestionably will give a well-known and highly respected book the much wider distribution that it deserves.

Man and the Winds. By E. AUBERT DE LA RUE. Pp. 206; figs. 26. Philosophical Library, New York, 1955. Price, $6.00.

The title suggests that this book is written as a popular one, which it is, but nevertheless it is also definitely a scientific contribution to the subject of winds, particularly as they affect mankind.

The first few chapters deal with the types of winds, followed by wind as a factor in determining climate and as a transporting agent. Other chapters deal with physiological effects and adapting dwellings to wind. Three other chapters deal with sand storms, sand erosion, and dunes. The author then treats of the wind as a source of energy, of sailing ships, and wind and aviation. The last chapters are concerned with benefits and drawbacks of the wind, the study of winds, the protection of fields and forests, and lastly, mythology and legend. There are five pages of bibliography and an index.

The North American Midwest. Edited by John H. Garland. Pp. 252; figs. 80. John Wiley & Sons, New York, 1955. Price, $8.00.

This book, composed of contributions from 15 authors, is a detailed study of the internal geographic structure of the Midwest. Part I, the Heart of a Continent, is a general introduction to the area, its people and its industry as a whole. Part II, Midwestern Elements, treats of climate, settlement, agriculture, industry, trade and transportation. Part III, the Inner Midwest, deals with the west-central and east-central lowlands, the eastern lower Great Lakes and the Upper Mississippi Valley. Part IV, the Midwestern Periphery, considers the Upper Great Lakes, the Ohio and Missouri Valleys and the Ozark upland. Each gives details of the people, climate, waterways, transportation, industry, minerals and cities.

The book is an excellent summary of the geography of a very important region.

BOOKS RECEIVED

KURT SERVOS

Annual Report. Pp. 81. Colorado Bureau of Mines, Denver, 1955. *Colorado mineral production in 1954 totalled more than $337 million.*

Seismic Wave Propagation and Pressure Measurements Near Explosions. GEORGE R. PICKETT. Pp. 78; figs. 21; tbls. 25. Colorado School of Mines Quarterly, Vol. 50, No. 4, Golden, 1955. Price, $1.50. *This mathematical treatment for geophysical engineers will be useful in extractive industries.*

The Structural and Tectonic History of India. M. S. KRISHNAN. Pp. 109; pls. 4; figs. 20. Mem. Geol. Survey of India, Vol. 81, Calcutta, 1953. Price, Rs. 2 As. 6.

Geology and Ground-Water Resources of Jewell County, Kansas. V. C. FISHEL and A. R. LEONARD. Pp. 152; pls. 12; figs. 24; tbls. 17. Kansas Geol. Survey Bull. 115, Topeka, 1955.

Clays and Clay Minerals. Pp. 498, illus. Nat. Acad. Sci.—Nat. Research Council, Pub. 327, Washington, 1955. *These proceedings of the Second National Conference on Clays and Clay Minerals contain 36 papers by 64 contributors. Several of the papers deal with the clay mineral composition of recent sediments and soils with special attention to the diagenetic changes that take place in such sediments and to weathering processes in soils. The chlorite and mixed-layer clay minerals, being the objects of intense and very recent investigations, have several important papers devoted to them. Papers are grouped roughly under the following subjects: genesis and occurrence of clays; methods of identification; fundamental crystallographic, chemical, and other studies; miscellaneous topics. A record of discussions follows each paper.*

Geothermal Steam for Power in New Zealand. Pp. 102; figs. 41; tbls. 10. New Zealand Dept. of Scientific and Industrial Research, Bull. 117, Wellington, 1955. Price, 15 *s.* *Total power potentiality of at least 200,000 kW is based on heat flow at the surface only (= 7,400 million B. t. u. per hour). Geologic map, 1:63,360.*

The Pittsburgh No. 8 and Redstone No. 8A Coal Beds in Ohio. R. M. DELONG. Pp. 49; figs. 12; tbls. 27. Ohio Geol. Survey, Rept. of Inv. 26, Columbus, 1955. Price, 50 cts. *Original reserves are estimated at 6.3 billion short tons.*

An Outline Survey of India's Economic Minerals. B. RAMA RAO. Pp. 39. Phoenix Press, Bangalore, 1955. *This non-technical outline is for the layman.*

Oklahoma Geology Notes. Pp. 12–23; tbls. 5. Oklahoma Geol. Survey, Norman, 1956.

Geology of the Montreal River Area. E. W. NUFFIELD. Pp. 32; figs. 11. Ontario Dept. of Mines, Vol. LXIV, Pt. 3, Toronto, 1956. *Uranium is the principal feature of economic interest. Geologic map, 1:31,680.*

Major Activities in the Atomic Energy Programs, July–December 1955. Pp. 200. U. S. Atomic Energy Comm., Washington, 1956. Price, 60 cts. *Part of the report summarizes this nation's participation in, and the results of, the International Conference on Peaceful Uses of Atomic Energy.*

The Geology and Mineral Deposits of the Potgietersrus Tin-fields. C. A. STRAUSS. Pp. 241; figs. 70; pls. 49; folders 13. Union of South Africa Dept. of Mines, Mem. 46, Pretoria, 1954. Price, 20 *s*. *This comprehensive report describes not only the important cassiterite but also significant deposits of molydenite and bastnaesite and constitutes, in addition, a valuable contribution to knowledge of the Bushveld.*

Bull. Geological Institution of the University of Upsala, Vol. XXXV. Pp. 243. University of Upsala, 1953–55. *Seven papers deal with stratigraphy and paleontology.*

California Division of Mines—San Francisco, 1955–56.

Journal of Mines and Geology, Vol. 51, No. 4. Pp. 293–465; figs. 19; pl. 1. Price, $1.00. *Petroleum, natural gas, cement, sand and gravel, stone, borates, Fe, W, Au, and salt account for a mineral production valued at $1.4 billion during 1953 in California. Geologic map of San Mateo County, 1:125,000.*

Bibliography of Marine Geology and Oceanography, California Coast. Special Rept. 44. R. D. TERRY. Pp. 131; figs. 2. Price, 75 cts.

Special Rept. 49. Radioactive Deposits in California. G. W. WALKER, T. G. LOVERING and H. G. STEPHENS. Pp. 38; figs. 6. Price, 50 cts.

Illinois Geological Survey—Urbana, 1955–56.

Circ. 205. Comparison of Mine Sizes of Southern Illinois Coals for Use in Metallurgical Coke. H. W. JACKMAN, R. L. EISSLER and F. H. REED. Pp. 10; tbls. 10.

Circ. 206. Mineral Production in Illinois in 1954. W. H. VOSKUIL and W. L. BUSCH. Pp. 59; figs. 11; tbls. 28. *In 1954 the value of Illinois mineral production was more than $500 million.*

Illinois Petroleum 73. Summary of Water Flood Operations in Illinois Oil Pools During 1954. P. A. WITHERSPOON, E. G. JACKSON, *et al.* Pp. 63; figs. 9; tbls. 3. *Secondary recovery during 1954 yielded 18 million bbl of oil from 232 water floods.*

Rept. of Inv. 188. Sandstone Resources of Extreme Southern Illinois. D. L. BIGGS and J. E. LAMAR. Pp. 21; pls. 2; figs. 2; tbls. 7. *Some southern Illinois sandstones, if properly processed, may yield silica sand possibly suitable for a variety of individual uses.*

Rept. of Inv. 189. Subsurface Stratigraphy of the Kinderhook Series in Illinois. L. E. WORKMAN and TRACEY GILLETTE. Pp. 46; pls. 2; figs. 20.

Rept. of Inv. 190. Some Experimental Factors that Modify Differential Thermograms of Bituminous Coal. K. E. CLEGG. Pp. 30; figs. 10; tbl. 1.

Rept. of Inv. 191. Groundwater Geology of the East St. Louis Area, Illinois. R. E. BERGSTROM and T. R. WALKER. Pp. 44; pls. 4; figs. 6; tbls. 2.

Rept. of Inv. 192. Pleistocene Deposits Along the Mississippi Valley in Central-Western Illinois. LELAND HORBERG. Pp. 39; pl. 1; figs. 15; tbl. 1.

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1955.

Rept. No. 165. Titanium Resources of Hokkaido, Japan. Pp. 155; pls. 4; figs. 53; tbls. 101. *All the Ti deposits of Hokkaido occur as placers. Total reserves are estimated at about 20 million metric tons. Text in Japanese, résumé in English.*

Rept. No. 166. Natural Gas in Takabe, Central Part of Shizuoka Prefecture, Japan. KOJI MOTOJIMA, KAZUYOSHI IDA, TOKIO MAKINO and TAKASHI MITSUNASHI. Pp. 58; figs. 43; pl. 1. *Natural dry gas is reserved in a crushed zone of a large underground thrust fault in marine lower Miocene rocks that overlie the fault.*

Missouri Geological Survey—Rolla, 1955.

Inf. Circ. 1. The Mineral Industry of Missouri in 1952. E. S. SMITH. Pp. 19; tbl. 1. *Total value of mineral production in 1952 was $143 million.*

Inf. Circ. 12. The Mineral Industry of Missouri in 1953. K. G. LARSEN. Pp. 18; tbl. 1; fig. 1. *Total value of mineral production in 1953 was $128 million.*

Rept. of Inv. 19. The Geology of the Fulton Quadrangle, Missouri. A. G. UNKLESBAY. Folded map. *Principal mineral resources are clay, coal and limestone.*

U. S. Bureau of Mines—Washington, D. C., 1955.

Distribution of Oven and Beehive Coke in 1954. Mineral Industry Surveys, Mineral Market Rept. 2452. Pp. 40; figs. 3; tbls. 6.

Minerals Yearbook Area Report, Vol. III, 1952. Pp. 1050, illus. Price, $3.75. *This volume contains chapters covering each of the States, Alaska, the Territories and island possessions in the Pacific, and the Territories and island possessions in the Caribbean, including Canal Zone. Total value of mineral production in continental U.S. during 1952 was $13.4 billion. Petroleum, coal, cement, natural gas and iron ore, in that order, led in order of quantity and value.*

U. S. Geological Survey—Washington, D. C., 1955.

Prof. Paper 274-E. Owl Creek (Upper Cretaceous) Fossils from Crowleys Ridge, Southeastern Missouri. L. W. STEPHENSON. Pp. 97–140; pls. 11; fig. 1. Price, $1.00.

Prof. Paper 274-C. Basal Eagle Ford Fauna (Cenomanian) in Johnson and Tarrant Counties, Texas. L. W. STEPHENSON. Pp. 53–67; pls. 4. Price, 75 cts.

Bull. 1009-I. Carnotite-bearing Sandstone in Cedar Canyon, Slim Buttes, Harding County, South Dakota. J. R. GILL and G. W. MOORE. Pp. 249–264; pls. 2; figs. 3; tbls. 4. Price, 35 cts. *The mineralized sandstone locally contains 0.23 pct. uranium.*

Bull. 1014. Stratigraphy of the Outcropping Cretaceous Rocks of Georgia. D. H. EARGLE. Pp. 101; pls. 3; figs. 17.

Bull. 1021. Some Curves from a Portable Differential Thermal Analysis Unit. C. J. PARKER, J. C. HATHAWAY and P. D. BLACKMON. Pp. 237–251; pl. 1; figs. 8; tbl. 1. Price, 25 cts. *The curves are for some standard clay minerals and minerals commonly associated with clay.*

Bull. 1027-F. Copper Deposits of Part of Helvetia Mining District, Pima County, Arizona. S. C. CREASEY and G. L. QUICK. Pp. 301–323; pls. 5; fig. 1;

tbls. 3. Price, $1.00. *The pyrometasomatic ore is mostly in late Paleozoic limestones. Structure controlled mineralization.*

Bull. 1027-K. Exploratory Drilling for Evidence of Zinc and Lead Ore in Dubuque County, Iowa. A. E. FLINT and C. E. BROWN. Pp. 471–499; figs. 8. Price, 20 cts. *Drilling verified the fact that the existence of favorable structures at depth can be inferred from studying the maps of the outcrops.*

Bull. 1028-B. Geology of Great Sitkin Island, Alaska. F. S. SIMONS and D. E. MATHEWSON. Pp. 21–43; pls. 2; figs. 2; tbl. 1. Price, $1.00. *Geologic map, 1:50,000.*

Bull. 1036-C. Rapid Analysis of Silicate Rocks. LEONARD SHAPIRO and W. W. BRANNOCK. Pp. 19–56; figs. 91; tbls. 5. Price, 20 cts. *This procedure is rapid, simple, direct, and less subjective than conventional methods and represents the first major improvement in technique since 1900.*

Bull. 1036-D. Correlation of Dioctahedral Potassium Micas on the Basis of Their Charge Relations. M. D. FOSTER. Pp. 57–67; fig. 1; tbls. 3. Price, 15 cts.

Water-Supply Paper 1354. Geology and Ground-water Resources of the Douglas Basin, Arizona. D. R. COATES and R. L. CUSHMAN. Pp. 56; pls. 5; figs. 5; tbls. 4. Price, $1.50.

Venezuela Ministerio de Minas—Caracas, 1955.

Revista de Minas e Hidrocarburos, Año VI, Num. 19. Pp. 352.

Revista de Minas e Hidrocarburos, Año VI, Num. 20. Pp. 58.

SCIENTIFIC NOTES AND NEWS

ARTHUR A. BAKER has been appointed Associate Director of the U. S. Geological Survey. He has served as Administrative Geologist in the Office of the Director since June 1953.

J. ROYCE announces the transfer of his geological office from 113 Crystal Avenue, Crystal Falls, Mich., to 207–211 Christie Bldg., Duluth 2, Minn. The office will continue as The Geological Dept., Picklands Mather & Co., with the transfer of J. T. Osborn and D. G. Harris, geologists.

The annual AIME PACIFIC NORTHWEST REGIONAL "METALS AND MINERALS CONFERENCE" will be held May 3–5 in Seattle, Wash. From a one-day program dealing with industrial minerals only, the sessions have expanded until now geology, industrial minerals, minerals beneficiation, mining, extractive metallurgy, iron and steel, and physical metallurgy are included. Geology papers will include: *Tectonic Patterns of the Western United States* by Peter Misch, University of Washington; *Granites of Magmatic Origin as Distinguished from Granites of Metasomatic Origin* by G. E. Goodspeed, University of Washington; *Localization of Ore in the Kootenay Arc* by M. S. Hedley and J. T. Fyles, British Columbia Dept. of Mines; and *The Work of the U. S. Geological Survey in the Pacific Northwest* by A. E. Weissenborn and M. R. Klepper, U. S. Geological Survey, Spokane, Wash.

THE PERMANENT COMMISSION ON AUTHOR'S ABSTRACTS OF THE INTERNATIONAL GEOLOGIC CONGRESS, at its meeting in Algiers in 1952, recommended the following procedure in submitting manuscripts: 1) as far as possible, editors in all countries should insist on an author's abstract accompany the original manuscript; 2) the abstract should be written in the language of the paper with a translation into at least one of the official languages of the Congress (English, French, German, Italian, Russian, Spanish); 3) the abstract should include conclusions concerning the various subjects considered in the paper; 4) the abstract should be printed with the paper, preferably at the beginning.

DONALD D. SMYTH has been in Chile inaugurating a geological study of the Braden Mine for the Kennecott Copper Co.

C. E. MICHENER, formerly chief geologist, exploration, has been appointed vice-president of the Canadian Nickel Co., a subsidiary of the International Nickel Co. of Canada, Ltd.

H. F. ZURBRIGG, formerly chief geologist, mines, is now also chief geologist, exploration, for International Nickel Co.

C. FRIEDLANDER has been appointed resident geologist for the Anglo American Corp. of South Africa, Ltd., with Chartered Exploration which is engaged in exploration in Northern Rhodesia.

J. E. ARMSTRONG, recently appointed head of the Geological Survey of Canada for British Columbia and the Yukon, has been elected vice-president of the Canadian Institute of Mining and Metallurgy for District 6 for 1956.

D. J. STRAW, JR., has been appointed assistant chief geologist for Rhodesian Asbestos, Ltd., Mashaba, Southern Rhodesia.

C. D. REYNOLDS has been appointed chief geologist and supervisor of the geology branch of the Mine Engineering Division of the Orinoco Mining Co., subsidiary of the U. S. Steel Corp.

The A.A.P.G. announces that THEODORE A. LINK became the 40th president of the American Association of Petroleum Geologists on April 26. Also on the 1956–57 Executive Committee are G. M. KNEBEL, past-president; BEN H. PARKER, vice-president; W. A. WALDSCHMIDT, secretary-treasurer; and, editor of the Bulletin will be W. C. KRUMBEIN, professor of geology, Northwestern University, Evanston, Ill. The new A.A.P.G. officers assumed the executive responsibilities of this 12,500 member organization at the close of the 41st annual meeting of the Association, which was held in the Conrad Hilton Hotel, Chicago, April 23–26.

RAYMOND CECIL MOORE, University of Kansas, Lawrence, has been elected an honorary member of the Society of Economic Paleontologists and Mineralogists.

Recipients of the AWARDS FOR THE BEST PAPER in the *Journal of Paleontology* and in the *Journal of Sedimentary Petrology* for 1954 are DONALD PARKINSON, Sutton Coldfield, Birmingham, England, for his paper entitled, "Quantitative Studies of Brachiopods from the Lower Carboniferous Reef Limestones of England," published in the *Journal of Paleontology*, Vol. 28, No. 3 (May, 1954); and HAROLD N. FISK, Humble Oil and Refining Co., Houston, Texas, CHARLES R. KOLB, Waterways Experimental Station, Vicksburg, Miss., EDWARD MCFARLAN, JR., Humble Oil and Refining Co., Houston, Texas, and LOUIS J. WILBERT, JR. (deceased), for their paper entitled, "Sedimentary Framework of the Modern Mississippi Delta," published in the Journal of Sedimentary Petrology, Vol. 24, No. 2 (June, 1954).

TAKAO SAMAKAMOTO, University of Tokyo professor of geology, is in Brazil studying the northern part of that country. Dr. Takao, who was commissioned by UNESCO, is regional vice-president of the American Economic Geologists in Asia.

CHARLES W. SMITH, geologist with American Smelting and Refining Company's exploration division for eastern United States, is being transferred to Peru where he will be resident geologist at the Quiricvilca unit of the Northern Peru Mining and Smelting Company.

JEAN DUGAS has been appointed resident geologist by the Quebec Department of Mines for the Rouyn-Noranda district of Northwestern Quebec. He succeeds Dr. J. E. Gilbert, the newly appointed resident geologist for the Montreal area.

CHARLES H. BURGESS has taken over, as vice-president of Bear Creek Mining Company, the domestic exploration subsidiary of Kennecott Copper Corp., and will make his headquarters in New York City.

HAROLD L. GRANT has been appointed vice-president and chief of mining engineering and geology of the Balcones Corporation Exploration and Drilling, San Antonio, Texas.

CHARLES WILL WRIGHT, mining consultant, returned to Sicily in February to do a consulting job for the Sicilian American Sulphur Company.

JOHN JESSE HAYES has been appointed chief geologist of the Marcona Mining Company in Peru. Dr. Hayes was formerly with the Orinoco Mining Company in Ciudad Bolivar, Venezuela, as a mining geologist.

C. FRIEDLAENDER is resident geologist with Chartered Exploration Ltd., a subsidiary of Anglo American Corp. of South Africa, in Lusaka, Northern Rhodesia.

JACK STONE has been named general manager of Fresnillo Company, Zacatecas, Mexico, as of January first.

W. R. NEWMAN, consulting geologist, announces the opening of an office in Toronto, at Suite 608, 133 Richmond Street West. He also retains his office at 103 Mercantile Building, Edmonton, Alberta.

RAYMOND CECIL MOORE, University of Kansas, Lawrence, has been elected honorary member of the Society of Economic Paleontologists and Mineralogists.

Board Chairman MELVIN H. BAKER of NATIONAL GYPSUM Co. revealed that development work will begin soon on a new multi-million dollar asbestos mine and plant at Thetford Mines, 75 miles south-west of Quebec. The new mine and plant will supply asbestos fibre to National Gypsum Company's three asbestos-cement plants at Millington, N. J., St. Louis, Mo., and New Orleans, La.

WILLIAM EMBRY WRATHER, associate editor of this Journal and former Director of the United States Geological Survey, has been chosen to receive the Sidney Powers Memorial Medal of the A.A.P.G., highest honor in the science of petroleum geology. The gold medal and scroll recognize distinguished and outstanding contributions to, and achievements in, petroleum geology. Wrather has received nearly every honor available to one in his profession, including the John Fritz medal, awarded by the four Founder Engineering Societies, sometimes referred to as the "medal for medallists" which he received in 1954; the Anthony Lucas Petroleum Medal of the American Institute of Mining and Metallurgical Engineers (1950); and U. S. Department of the Interior Distinguished Service Award (1955). He was made Honorary Member of the American Association of Petroleum Geologists in 1943; and a life member of the Board of Trustees of the National Geographic Society in 1951. The following citation is printed on the scroll which accompanies the gold medal: "For outstanding contribution through wise and vigorous leadership as a pioneer in the field of petroleum geology; for distinguished achievement through the early successful application of geologic principles to oil finding; and for effective direction through arduous wartime years of critical geologic activities of Government."

The Fifth National Clay Conference will be held at the University of Illinois, Urbana, Ill., Oct. 8, 9 and 10, 1956. The conference is sponsored annually by the Clay Minerals Committee of the National Academy of Sciences—National Research Council, under the chairmanship of Prof. R. E. Grim of the University of Illinois. Contributed papers on subjects related to clay mineralogy or technology will be welcome. Titles for inclusion in the program must be received by May 1, and short informative abstracts will be required by June 15. Titles and abstracts may be sent to Dr. W. F. Bradley, Illinois Geological Survey, Urbana, Illinois. More detailed announcements will be distributed about April 1.

ADVERTISEMENTS

Patrons of this journal are requested to refer to ECONOMIC GEOLOGY AND THE BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS when consulting advertisers.

Announcing the Issuance of—

FIFTIETH ANNIVERSARY VOLUME

ECONOMIC GEOLOGY

1905–1955

CONTENTS

Part I

FOREWORD ii
ECONOMIC GEOLOGY ..... *Alan M. Bateman* 1
METALLOGENETIC PROVINCES AND EPOCHS ..... *F. S. Turneaure* 38
THERMAL SPRINGS AND EPITHERMAL ORE DEPOSITS ..... *Donald E. White* 99
THE CLASSIFICATION OF ORE DEPOSITS ..... *James A. Noble* 155
STRUCTURE OF HYDROTHERMAL ORE DEPOSITS ..... *H. E. McKinstry* 170
THE ZONAL THEORY OF ORE DEPOSITS ..... *Charles F. Park, Jr.* 226
TEMPERATURES IN AND NEAR INTRUSIONS ..... *T. S. Lovering* 249
SYNTHETIC MINERALS ..... *W. A. Weyl* 282
HYDROTHERMAL ALTERATION AS A GUIDE TO ORE ..... *George M. Schwartz* 300
OXIDATION OF COPPER SULFIDES AND SECONDARY SULFIDE ENRICHMENT *Charles A. Anderson* 324
METHODS AND PROBLEMS OF GEOLOGIC THERMOMETRY ..... *Earl Ingerson* 341
SEDIMENTARY DEPOSITS OF RARE METALS ..... *Konrad B. Krauskopf* 411
ORIGIN OF URANIUM DEPOSITS ..... *V. E. McKelvey, D. L. Everhart and R. M. Garrels* 464

Part II

ENGINEERING GEOLOGY—A FIFTY YEAR REVIEW ..... *Robert F. Legget* 534
INFLUENCE OF GEOLOGICAL FACTORS ON THE ENGINEERING PROPERTIES OF SEDIMENTS ..... *Karl Terzaghi* 557
RECENT DEVELOPMENTS IN CLAY MINERALOGY AND TECHNOLOGY *Ralph E. Grim* 619
PROPERTIES OF CALCIUM AND MAGNESIUM CARBONATES AND THEIR BEARING ON SOME USES OF CARBONATE ROCKS ..... *D. L. Graf and J. E. Lamar* 639
THE QUANTITATIVE APPROACH TO GROUND-WATER INVESTIGATIONS *John G. Ferris and A. Nelson Sayre* 714
TIME OF PETROLEUM ACCUMULATION ..... *A. I. Levorsen* 748
COAL PETROLOGY ..... *C. E. Marshall* 757
THE USE OF GAMMA RAY MEASUREMENTS IN PROSPECTING *William L. Russell* 835
ECONOMIC APPLICATIONS OF PALEOECOLOGY ..... *Samuel P. Ellison* 867
GEOPHYSICS APPLIED TO PROSPECTING FOR ORES ..... *Louis B. Slichter* 885
MINOR ELEMENTS IN SOME SULFIDE MINERALS ..... *Michael Fleischer* 970
THE STUDY OF PEGMATITE DEPOSITS ..... *Richard H. Jahns* 1025–1130

Order from:

ECONOMIC GEOLOGY PUBLISHING COMPANY

105 Natural Resources Building, Urbana, Illinois

Price to Subscribers (including members, non-member Journal subscribers, and students whether subscribers or not) $6.00
Price to Non-Subscribers to Journal 8.00

for precision microscopy with polarized light

Leitz **POLARIZING** *microscopes*

In such fields as geology, mineralogy, petrography, coal research, plastics, biology, chemistry and biochemistry, there is a Leitz *POLARIZING* Microscope designed to meet every requirement. No other manufacturer offers such a wide variety of polarizing microscopes and accessories, built to the highest standards of quality and design.

Leitz polarizing microscope, Model AM

- Rotating anastigmatic tube analyzer for improved image quality and freedom from eyestrain.
- Polarizing tube accommodates large field-of-view eyepieces.
- Bertrand auxiliary lens with iris diaphragm can be raised and lowered.
- Rapid clutch changer and centering device for permanent centering of objectives.
- Large substage illuminating apparatus with two-diaphragm condenser and polarizer, either calcite or filter.
- Rotating object stage on ball bearings, with vernier reading to 1/10th°
- Rack and pinion motion for raising and lowering stage, to accommodate large opaque specimens.
- Polarizing vertical illuminator easily attachable.

E. LEITZ, INC., Dept. Q-5
468 Fourth Ave., New York 16, N. Y

Please send brochure on Leitz *POLARIZING* Microscopes.

Name_____

Street_____

City_____ Zone____ State_____

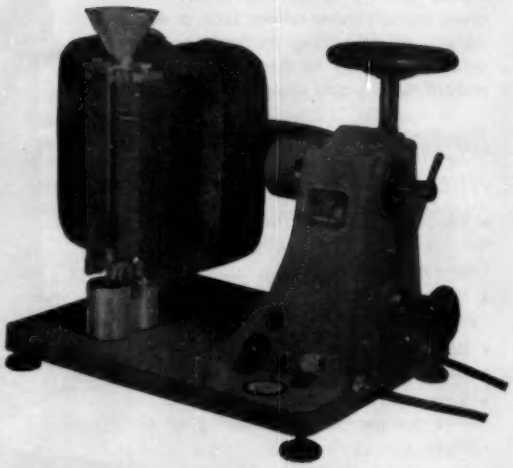
05588

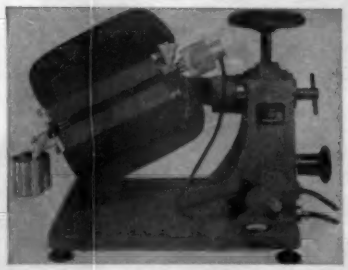
E. LEITZ, INC., 468 FOURTH AVENUE, NEW YORK 16, N. Y.
Distributors of the world-famous products of Ernst Leitz, Wetzlar, Germany
LENSES • CAMERAS • MICROSCOPES • BINOCULARS

FRANTZ ISODYNAMIC Magnetic SEPARATOR

Available with Vertical Fall Attachments

This arrangement is suitable for free-flowing sands. A delicate separation is made possible by the special configuration of the pole pieces which give a magnetic field resulting in forces depending only on susceptibility and not on the position of the particles in the field. Heavy sands can be fed at rates up to 20 lb. per hour.





the ORIGINAL

MAGNETIC SEPARATOR

of this type

The Isodynamic Separator, as usually used with vibrating inclined chute, is shown at the left. It is suited to the most precise separations over a wide range of particle sizes (some as small as 25 microns) at slow feed rates.

S. G. FRANTZ Co., Inc. . . . Engineers

P.O. Box 1138
Trenton 6, New Jersey, U.S.A.

Cable Address:
MAGSEP, Trentonnewjersey

A COMPLETE PRINTING SERVICE

GOOD PRINTING does not just happen; it is the result of careful planning. The knowledge of our craftsmen, who for many years have been handling details of composition, proofreading, presswork and binding, is at your disposal. For seventy-five years we have been printers of scientific and technical journals, books, theses, dissertations and works in foreign languages. Consult us about your next printing job.

• PRINTERS OF • ECONOMIC GEOLOGY

LANCASTER PRESS, Inc.

PRINTERS • BINDERS • ELECTROTYPERS

ESTABLISHED 1877 LANCASTER, PA.

Announcing

SPECIAL STUDENT SUBSCRIPTION RATES

ECONOMIC GEOLOGY

and the Bulletin of the Society of Economic Geologists:

An international journal devoted to the field of Economic Geology

Edited by ALAN M. BATEMAN

Business Editor, MORRIS M. LEIGHTON

8 issues per year

Regular subscription rate, $6.50, student rate, $4.00

(Canadian postage, 30¢)

Students registered in geology courses in the United States and Canada may send for application blank to: **Economic Geology Publishing Company, 121 Natural Resources Building, Urbana, Illinois.**

ANNOTATED BIBLIOGRAPHIES OF ECONOMIC GEOLOGY

Available—Vols. I–XXVII (1938–1954).

Vol. XXVIII (1955) current volume for 1956.

Price $5.00 per volume anywhere in the world thru Volume 27.
Effective Volume 28—price change to $6 per volume.

General Index, Vols. I–XXV, in preparation.

Order now from

ECONOMIC GEOLOGY PUBLISHING COMPANY

105 Natural Resources Building Urbana, Illinois

ECONOMIC GEOLOGY JOURNAL INDEX to Vols. XXXI–XL (1936–1945)—published September, 1947
Price $2.00

Also available Index to Vols. I–XX (1906–1926) —$3.00
Index to Vols. XXI–XXX (1927–1935)— 2.00
Index to Vols. XLI–L in preparation

ECONOMIC GEOLOGY PUBLISHING COMPANY

105 Natural Resources Building Urbana, Illinois

FOR SALE

BACK VOLUMES OF ECONOMIC GEOLOGY

From Stock:

Complete Volumes: 3, 6, 7, 8, 9, 10, 11, 15, 22, 25 @ $15 per volume

Complete Volumes: 26, 27, 28, 29, 30, 31, 32, 33, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 49, 50 @ $12 per volume

Incomplete Volumes but from which certain issues are still available (some of them almost complete:
1, 2, 4, 5, 12, 13, 14, 16, 17, 18, 19, 21, 23, 24, 34, 48
@ $2.25 per issue

Secondhand copies suitable for binding:

Complete Volumes: 30, 35, 36, 41, 42, 43, 44, 46 @ $5 per volume

Incomplete Volumes from which certain issues are available:
2, 4, 5, 7, 8, 10, 11, 14, 15, 17, 18, 19, 22, 23, 24, 25, 26, 27, 28, 29, 31, 34, 37, 38, 39, 40, 45, 47, 48
(over 100 issues) @ 50 cents per issue

Inquire:

Economic Geology Publishing Company
105 Natural Resources Building
Urbana, Illinois

Economic Geology issues devoted to articles on uranium or containing an article thereon:

Vol. 51, No. 1—ROGER Y. ANDERSON and EDWIN B. KURTZ, JR.: **A Method for the Determination of Alpha-Radioactivity in Plants as a Tool for Uranium Prospecting** $1.25

Vol. 50, No. 2—**Uranium issues** (12 articles on uranium) 2.25

Vol. 46, No. 4—WILLIAM L. RUSSELL and S. A. SCHERBATSKOY: **The Use of Sensitive Gamma Ray Detectors in Prospecting** 2.25

Vol. 45, No. 2—GEORGE M. BROWNELL: **Radiation Surveys with a Scintillation Counter** 2.25

Order from:

Economic Geology Publishing Company
105 Natural Resources Bldg.
Urbana, Illinois

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

BULLETIN GEODESIQUE

Quarterly Journal published by the Central Office of the International Association of Geodesy, 19, rue Auber, Paris, FRANCE

The scientific articles appearing in the BULLETIN GEODESIQUE are prepared by the foremost geodesists and geophysicists in the world and deal with the following subjects: *Mathematical geodesy* (*instruments, observations, calculation and adjustment of triangulation*), *Astronomical determination of geographic positions, Dynamical geodesy* (*gravimetry, figure of the Earth, earth tides, isostasy, etc.*) *Leveling.* It contains also a section of book notices.

Application for subscription to be addressed to: International Association of Geodesy, 19, rue Auber, PARIS, 9e. Annual subscription: $2.65 (payable by check drawn to the order of the International Association of Geodesy, the remittance to be sent to the International Association of Geodesy, care American Geophysical Union, 1530 P Street N.W. WASHINGTON 5, D.C.) or 13 shillings (payable by a deposit in sterling to the credit of the "Association Internationale de Géodésie" at the National Provincial Bank, Avenue Branch, SOUTHAMPTON, England.)

COMPREHENSIVE INDEX

OF THE PUBLICATIONS OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, 1917–1945

By DAISY WINIFRED HEATH

603 PAGES. PRICE $4.00 (TO MEMBERS, $3.00)

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

Box 979, Tulsa 1, Oklahoma

LABORATORY FOR ROCK ANALYSIS

Chemical analyses of rocks and minerals made with accuracy required for research. Commercial work cannot be accepted.

SAMUEL S. GOLDICH, in charge

Department of Geology and Mineralogy, University of Minnesota, Minneapolis 14, Minnesota

---

W. HAROLD TOMLINSON

Petrographic Laboratory

260 N. ROLLING RD., SPRINGFIELD, PA. (Delaware Co.)

SECTIONS EXAMINATIONS

Petrographic examinations and reports

PETROGRAPHIC ROCK THIN SECTIONS

•

MOUNTED POLISHED ORE SPECIMENS

Fred Roberts » » »

MICROSCOPIC MINERAL SECTION TECHNICIAN

1106 W. NEWMARK AVENUE, MONTEREY PARK, CALIFORNIA

SWAN ENGRAVING COMPANY

PHOTO ENGRAVERS COMMERCIAL ARTISTS

BRIDGEPORT, CONN. NEW HAVEN, CONN

POUGHKEEPSIE, N.Y.

GEOPHYSICAL CASE HISTORIES, VOLUME I, 1948
(Second printing, 1949)

Edited by L. L. Nettleton, Past President

A collection of 60 papers by 61 authors on geophysical observations made under a wide variety of field circumstances. This is the first volume of a series designed to provide material by which geophysical surveys can be judged from later development and thus aid in the interpretation and evaluation of other geophysical work.

680 pages 7 x 10 Fully illustrated Cloth bound

COMPLETE TITLE INDEX CROSS-REFERENCED TO CLASSIFIED INDEX OF ALL MAPS AND FIGURES

PRICE $7.00 POSTPAID IN U.S.A.

SOCIETY OF EXPLORATION GEOPHYSICISTS
624 SOUTH CHEYENNE TULSA, OKLAHOMA

An A.A.P.G. Book!

POSSIBLE FUTURE PETROLEUM PROVINCES OF NORTH AMERICA

UP-TO-DATE PICTURE OF UNDISCOVERED RESOURCES, SYMPOSIUM REPRESENTING THE WORK OF 17 GEOLOGICAL SOCIETIES, 13 FEDERAL, STATE, AND PROVINCIAL GEOLOGICAL SURVEYS, OR ANALOGOUS ORGANIZATIONS, REPRESENTATIVES OF 33 OR MORE OIL COMPANIES AND 8 UNIVERSITIES, AND 24 CONSULTING GEOLOGISTS.

- First published in A.A.P.G. Bulletin, February, 1951
- Complete symposium, 6 x 9 inches, bound in cloth
- 360 pages, 153 line drawings

PRICE: $4.00 POSTPAID
(Member price, $2.50)

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
BOX 979, TULSA 1, OKLAHOMA, U.S.A.

BOOKS IN GEOLOGICAL SCIENCE

Address ECONOMIC GEOLOGY, Urbana, Ill. Books not in this list (except the publications of official Surveys and those of the Geological Society of America) will be furnished at Publishers' prices.

AREAL GEOLOGY AND REGIONAL

Geological Survey of Great Britain. By EDWARD B. BAILEY. 1952. Pp. 278. Pls. 4. Figs. 39... 4.00

The Geology of the Commonwealth of Australia. By T. W. E. DAVID. 1950. Three volumes..... $50.00

I. Historical Geology. Pp. 720. Pl. 57. Figs. 208.

II. Physiography. Pp. 645. Pl. 28. Figs. 164.

III. Maps: Geological Map of the Commonwealth of Australia (11 sections on 4 sheets), and Geological Sketch-Map of Australian New Guinea (1 section).

Late Cenozoic Erosional History of the Raton Mesa Region. By WILLIAM S. LEVINGS. 1951. Pp. 111. Illus. 31. 16 large contour and cross-section maps..... 2.50

Historical Geology of the Antillean-Caribbean Region. By CHARLES SCHUCHERT. 1935. Pp. 811. Illus. 6 x 9½..... 15.00

Los Yacimientos Minerales de Bolivia. By FEDERICO AHLFELD. 1954. Pp. 277..... 6.00

The Geology of the British Empire. By F. R. C. REED. 2nd Ed. 1949. Pp. 764. 26 sections and maps, including 15 folders..... 14.00

Structural History of the East Indies. By J. H. F. UMBGROVE. 1949. Pp. 63. Figs. 68..... 8.50

The Geology of Indonesia. By R. W. VAN BEMMELEN. 1949.

Vol. I: General Geology of Indonesia and Adjacent Archipelagos. Pp. 732. Tables 124.

Vol. II: Economic Geology of Indonesia. Pp. 265. With 52 figures and 56 tables.

Price of the two volumes and portfolio. Cloth.....75 Guilders

Geology of India. 3rd Ed. By D. N. WADIA. 1953. Pp. 552. Pl. 18. 6 maps, 25 x 30 full color geological map of India..... 10.00

Geology of China. By J. S. LEE (LI, SSU-KUANG). 1939. Pp. 528. Illus. 93. Cloth..... 4.50†

Geology of South Africa. 3rd Ed. By ALEXANDER L. DU TOIT. 1952. Pp. 556. Pl. 41. Figs. 68. Geol. Map..... 10.00

CRYSTALLOGRAPHY AND MINERALOGY

Crystal Growth. By H. E. BUCKLEY. 1951. Pp. 571..... 10.00

Crystals and the Polarizing Microscope. 2nd Ed. By N. H. HARTSHORNE and A. STUART. 1950. Pp. 473. Diags. 313..... 9.50

Optical Crystallography. 2nd Ed. By E. E. WAHLSTROM. 1951. Pp. 206. Figs. 209..... 5.00

A Text Book on Crystal Physics. By W. A. WOOSTER. 1949. Pp. 295. 108 Text Figs. Tables 44 5.50

X-Rays in Practice. By W. T. SPROULL. 1946. Pp. 603. Illus..... 8.00

Crystal Structures. Volume I. By RALPH W. G. WYCKOFF. 1948. Pp. 256. Illus. 66. 122 pages of tables. Loose-leaf with binder..... 8.00

Supplement Volume I: 1951. 72 text pages. 64 pages of tables..... 4.00

Crystal Structures. Volume II. 1951. By RALPH W. G. WYCKOFF. 253 text pages, 74 illus. 256 pages of tables. With binder..... 10.00

Supplement II: 1953. 30 Pp. 64 tables..... 4.00

Crystal Structures. Volume III. 1953. By Ralph W. G. Wyckoff. 244 Pp., 176 Illus. 220 tables 14.50

The Crystalline State. Edited by W. H. BRAGG.

Vol. 1: A General Survey. New Ed. By L. BRAGG. 1949. Pp. 352. Illus..... 5.50

Vol. 2: Optical Principles of the Diffraction of X-Rays. By R. W. JAMES. 1949. Pp. 623..... 13.00

Vol. 3: Determination of Crystal Structures. By Lipson and Cochran. 1954. 345 Pp..... 8.00

The Barker Index of Crystals.—A Method for the Identification of Crystalline Substances. By M. W. PORTER and R. C. SPILLER. 1951. Pp. 1500.

Vol. I, Part 1..... 6.00

Part 2..... 18.00

Phase Microscopy. By A. BENNETT and others. 1951. Pp. 320..... 9.00

X-Ray Analysis of Crystals. By J. M. BIJVOET and others. Translated by H. LITTMAN FURTH. 2nd Ed. 1951. Pp. 310. Illus..... 8.00

An Introduction to Luminescence of Solids. By HUMBOLDT W. LEVERENZ. 1950. Pp. 569; this. 23; figs. 143..... 15.00

X-ray Crystallography. 4th Ed. By R. W. JAMES. 1950. Pp. 88..... 1.75

X-ray Crystallography. By MARTIN J. BUERGER. 1942. Pp. 531. Illus. 252..... 9.50

Imperfections in Nearly Perfect Crystals. By W. SHOCKLEY. 1952. Pp. 490; figs. 175..... 9.00

Elements of Optical Mineralogy. By ALEXANDER N. WINCHELL.

Pt. I. Principles and Methods. 5th Ed. 1937. Pp. 263. Illus. 305..... 5.00

Pt. II. Description of Minerals. 4th Ed. 1951. Pp. 551..... 12.50

Pt. III. Determinative Tables. 2nd Ed. 1939. Pp. 244..... 6.50

Optical Mineralogy. 2nd Ed. By AUSTIN F. ROGERS and PAUL F. KERR. 1942. Pp. 390. Figs. 369. Cloth..... 6.50

Tables for Microscopic Identification of Ore Minerals. By W. UYTENBOGAARDT. 1951. Pp. 242.. 5.00

Stereograms for the Determination of Plagioclase Feldspars in Random Sections. By W. NIEUWENKAMP. 1948. Pp. 29..... 6.40

Mineralogy. 4th Ed. By E. H. KRAUS, W. F. HUNT, and L. S. RAMSDEL. 1951..... 8.00

Clay Mineralogy. By RALPH E. GRIM. 1953. Pp. 384. Fig. 121. Tables 46..... 9.50

(*Continued on Page xi*)

(*Continued from Page x*)

BOOKS IN GEOLOGICAL SCIENCE

CRYSTALLOGRAPHY AND MINERALOGY (Continued)

Dana's System of Mineralogy. By CHARLES PALACHE, HARRY BERMAN and CLIFFORD FRONDEL.
Vol. I. Elements, Sulfides, Sulfosalts, Oxides. 7th Ed. 1944. Pp. 834. Illus. 14.00
Vol. II. Halides, Carbonates, etc. 7th Ed. 1951. Pp. 1124. Illus. 16.00

Manual of Mineralogy. By J. S. DANA—16th Ed. Revised by C. S. HURLBUT. 1952. Pp. 539.. 7.00

Minerals and How to Study Them. 3rd Ed. By EDWARD S. DANA. Revised by CORNELIUS S. HURLBUT, JR. 1949. Pp. 323. Illus. 384. ..... 5.75

Elements of Mineralogy. 24th Ed. By FRANK RUTLEY (Revised by H. H. READ). 1953. Pp. 535. Illus. 138. ..... 2.50

Textbook of Mineralogy. 13th Rev. Ed. By KLOCKMANN. 1948. Pp. 674. Illus. 606...Stitched 11.38
.....Bound 11.90

Elements of Mineralogy Emphasizing the Variations in Minerals. By ALEXANDER N. WINCHELL. 1942. Pp. 535. ..... 7.65

Dana's Textbook of Mineralogy. 4th Ed. Revised by WM. E. FORD. 1932. Pp. 851. Illus., Diagrams. 8.00

A Field Guide to Rocks and Minerals. By FREDERICK H. POUGH. 1953. Pp. 331. 12 Color Pls., 32 black and white numerous crystal drawings 3.75

Rutley's Elements of Mineralogy. By H. H. READ. 25th ed. Pp. 525, figs. 137. ..... 2.50

Introduction to Study of Minerals and Rocks. 3rd Ed. By AUSTIN L. ROGERS. 1937. Pp. 626. Illus. 7.50

Handbook of Mineralogy, Blowpipe Analysis and Geometrical Crystallography. Combined Ed. By G. MONTAGUE BUTLER. 1918. Pp. 546. 4½ x 7. ..... 6.50

The Colloid Chemistry of the Silicate Minerals. By C. EDMUND MARSHALL. 1953. Pp. 195. Illus. 5.80

Colorimetric Determination of Traces of Metals. By ERNEST B. SANDELL. 1944. 2nd Ed. Revised. Pp. 693. Illus. 83, Tables 107. ..... 10.50

How to Know Minerals and Rocks. By RICHARD M. PEARL. 1955. Pp. 192. Figs., Keys. 3.50

Minerals and Rocks. By RUSSELL D. GEORGE. 1943. Pp. 595. Figs. 150. Pls. 48. ..... 6.00

Quartz Family Minerals. By H. C. DAKE, F. L. FLEENER, and B. H. WILSON. 1938. Pp. 304. .... 4.75

Mineral Collectors Handbook. By RICHARD M. PEARL. 1947. Pp. 297. ..... 3.75

A Handbook of Gem Identification. 4th Rev. Ed. By RICHARD T. LIDDICOAT, JR. 1953. Pp. 349. Illus. 117. ..... 5.00

Jewelry, Gem Cutting, and Metalcraft. 3rd ed. By WILLIAM T. BAXTER. 1950. Pp. 360. Illus. 173. ..... 4.50

Gem Testing. By B. W. ANDERSON. 1948. Pp. 256. Illus. 55. ..... 5.00

Dictionary of Gems and Gemology. 4th Ed. By R. M. SHIPLEY. 1951. Pp. 260. ..... 5.50

A Key to Precious Stones. 2nd Ed. By L. J. SPENCER. 1946. Pp. 237. 57 Illus. 8 pp. pls. 3.50

Gems and Gem Materials. 5th Ed. By EDWARD H. KRAUS and C. B. SLAWSON. 1947. Pp. 332. Illus. 6.00

Colorado Gem Trails. By R. M. PEARL. 3rd Ed. 1953. Pp. 128. Photos; Sketch maps 2.25

Popular Gemology. By RICHARD M. PEARL. 1948. Pp. 316. Figs. 115. ..... 5.50

A Handbook of Precious Stones. By RAO BAHADUR DR. L. A. N. IYER. 1948. Pp. 188. Figs. 39. 3.15

A Roman Book on Precious Stones. By SYDNEY H. BALL. 1950. Pp. 360. ..... 6.75

ECONOMIC GEOGRAPHY

Geography of North America. By GEORGE J. MILLER, ALMON E. PARKINS and BERT HUDGINS. 1954. 3rd Ed. Pp. xi + 664. figs. 290, tbls. 25. ..... 7.50

Geography of the Northlands. By GEORGE H. T. KIMBLE and DOROTHY GOOK. 1955. Pp. 534, Illus. 10.00

Industrial and Commercial Geography. 3rd Ed. By J. RUSSELL SMITH and M. O. PHILLIPS. 1946. Pp. 978. ..... 6.50

Economic Geography: New Edition. By CHARLES C. COLBY and ALICE FOSTER. 1954. Pp. 685.. 3.72

World Population and Production. By W. S. WOYTINSKY and E. S. WOYTINSKY. 1953. Pp. 1268, tbls. 338, pls. 338. ..... 12.00

Geography of Living Things By M. S. ANDERSON. 1952. Pp. 202. Figs. 5. ..... 2.75

Fundamentals of Economic Geography. 3rd Ed. Rev. Ed. by NELS A. BENGTSON and W. VAN ROYEN. 1950. Pp. 574. Photo. 142. Maps 76. Charts, etc. 150. ..... 7.90

Economic and Industrial Geography. By A. M. NIELSEN. 1950. Pp. 728. ..... 6.75

Principles of Economic Geography. By ELLSWORTH HUNTINGTON assisted by FRANK E. WILLIAMS, SAMUEL VAN VALKENBERG, and STEPHEN S. VISHER. 1940. Pp. 715. Illus. 6.00

Physical Elements of Geography. 3rd Ed. By V. C. FINCH and G. T. TREWARTHA. 1949. Pp. 696. Illus. 6.25

Advanced Atlas of Modern Geography. By JOHN BARTHOLOMEW. 1950. Pp. 155, 108 of which are maps. Printed in Great Britain at the Geographical Institute. 9.50

Conserving Natural Resources—Principles and Practice in a Democracy. By SHIRLEY W. ALLEN. 1955. Pp. 347, Figs. 168. ..... 5.50

Conservation in the United States. 3rd Ed. By AXEL F. GUSTAFSON, C. H. GUISE, W. J. HAMILTON, JR., and H. RIES (Members of the faculty of Cornell University). 1949. Pp. 344. Illus. 254.. 5.00

(*Continued on Page xii*)

(*Continued from Page xi*)

BOOKS IN GEOLOGICAL SCIENCE

ECONOMIC GEOGRAPHY (Continued)

The Pacific Northwest. By O. W. FREEMAN, H. H. MARTIN, and others. 2nd Ed. 1954. Pp. 542. Illus. 6.00

Atlas of Pacific Northwest; Resources and Development. 1953. Pp. 130. Maps 72 ..... 1.75

The U.S.S.R.—A Geographical Survey. By J. S. GREGORY and D. W. SHAVE. 1946. Pp. 636. Illus. 6.00

ECONOMIC GEOLOGY

The Formation of Mineral Deposits. By ALAN M. BATEMAN. 1951. Pp. 334. Illus. 6.25

Mining Geology. By HUGH E. MCKINSTRY. 1948. Pp. 680 ..... 10.00

Principles of Field and Mining Geology. By J. DONALD FORRESTER. 1946. Pp. 647. Illus. 316. 8.75

Economic Mineral Deposits. 2nd Ed. By ALAN M. BATEMAN. 1950. Pp. 915. Illus. 308 ..... 8.75

Textures of the Ore Minerals and their Significance. By A. B. EDWARDS. 2nd Ed. 1954. Pp. 242. 204 Illus. 10.00

Non-Metallic Minerals. 2nd Ed By RAYMOND B. LADOO and W. M. MYERS. 1951. Pp. 605 ... 11.00

Minerals and Mineral Deposits. By W. R. JONES and D. WILLIAMS. 1948. Pp. 255. Figs. 36. Maps. Bibliography. Tables 1.20

Mineral Deposits. 4th revised Ed. By WALDEMAR LINDGREN. 1933. Pp. 930 ..... 11.00

Minerals for Atomic Energy. By ROBERT D. NININGER. 1954. Pp. 384, Illus. 7.50

Ore Genesis. By J. S. BROWN. 1948. Pp. 204. Illus. 4 ..... 3.50

Ore Deposits as Related to Structural Features. Edited by WALTER H. NEWHOUSE. 1942. Pp. 292. Illus. 250. Cloth, 9 x 12 ..... 8.50

Structural Geology of Canadian Ore Deposits (Symposium volume published in commemoration of 50th Anniversary of the Canadian Institute of Mining and Metallurgy). 1951. Pp. 930 (132 separate papers as written by over 100 Canadian mining executives). Illus. 300 ..... 10.00
Price to qualified students 8.00

URANIUM (Where it is and how to find it). By P. D. PROCTOR, E. P. HYATT, and K. C. BULLOCK. 1954. Pp. 96. 18 full pages maps. Illus. ..... Cloth 2.50
Paper 2.00

Minerals, for the Chemical and Allied Industries. By SIDNEY J. JOHNSTONE. 1954. Pp. 692 ..... 11.50

Copper Venture. By KENNETH BRADLEY. 1952. Pp. 112. Illus. and Maps 2.30

Tin 1954: A Review of the World Tin Industry. By INTERNATIONAL TIN STUDY GROUP. 1955. Pp. 56. Charts 23 ..... 1.00

Cobalt. (ACS Monograph, 108) By ROLAND S. YOUNG. 1948. Pp. 180. Illus. 5.50

Lazarus Erker's Treatise on Ores and Assaying. By A. G. SISCO and C. S. SMITH. 1952. Pp. 360. Illus. 41 ..... 10.00

Occurrence and Production of Molybdenum. By J. W. VANDERWILT. 1942. Pp. 78. Paper 1.50

Mineral Resources of China. By V. C. JUAN. 1946. Pp. 75. Illus. Paper ..... .75

The Coalfields of Great Britain. By SIR ARTHUR TRUEMAN. 1954. Pp. xi + 396, pls. 7, figs. 106, tbls. 5 ..... 15.00

Coal: Its Formation and Composition. By WILFRED FRANCIS. 1954. Pp. 567 ..... 17.50

Coal. 2nd Ed. By ELWOOD S. MOORE. 1940. Pp. 473. Pl. 20. Figs. 120 ..... 8.50

Coals and Bitumens. By S. I. TOMKEIEFF. 1954. Pp. 122. Illus. 4 ..... 3.00

Progress in Coal Science. Vol. I. By D. H. BANGHAM (ed.). 1950. Pp. 469. Illus. 32. Tables 29, Pl. 12 ..... 7.00

The Nature and Origin of Coal and Coal Seams. By ARTHUR RAISTRICK and C. E. MARSHALL. 1939. Pp. 312. Figs. 100 ..... 2.60

Coal Through the Ages. By H. N. EAVENSON. 1939. Pp. 123 ..... 1.50

Coalmining. By I. C. F. STATHAM. 1951. Pp. 564. Illus. 22s/6d

Geology of Petroleum. By A. I. LEVORSEN. 1954. Pp. 720, illus. 327 ..... 8.00

Principles of Petroleum Geology. By CECIL G. LALICKER. 1949. Pp. 377. Illus. Pl. Maps 5.00

Petroleum Geology. By KENNETH K. LANDES. 1951. Pp. 660. Illus. 241 ..... 10.00

Principles of Petroleum Geology. By W. L. RUSSELL. 1951. Pp. 508. Figs. 132 ..... 7.50

How Oil is Found. By W. A. VER WIEBE. 1951. Pp. 247. Illus. 312 ..... 8.50

Fundamental Research on Occurrence and Recovery of Petroleum, 1950–51. By LLOYD E. ELKINS. 1953. Pp. 263 ..... 6.00

Principles of Petroleum Geology. By E. N. TIRATSOO. 1951. Pp. 449 ..... 7.50

Practical Oil Geology. 6th Ed. By DORSEY HAGER. 1951. Pp. 466. 5¼ x 7½. Illus. 8.00

Structure of Typical American Oil Fields. Vol. III. 1948. Pp. 516. Illus. 219 ..... 4.50

Petroleum Microbiology. By ERNEST BEERSTECHER, JR. 1954. Pp. 375; figs. 71 ..... 8.00

Oil Property Valuation. By PAUL PAINE. 1942. Pp. 204 ..... 5.50

Review of Petroleum Geology in 1947. By F. M. VAN TUYL, W. S. LEVINGS, and others. 1948. Pp. 334 ..... 3.00

Physical Principles of Oil Production. By MORRIS MUSKAT. 1949. Pp. 922. Illus. 15.00

Oil and Gas Production. By THE ENGINEERING COMMITTEE OF THE INTERSTATE OIL COMPACT COMMISSION. Pp. 140. Illus. with charts, graphs, and tables 2.75

Practical Petroleum Engineers Handbook. 3rd Ed. 1951. Pp. 654. Illus. by JOSEPH ZABA and W. T. DOHERTY 11.00

(*Continued on Page xiii*)

(Continued from Page xii)

BOOKS IN GEOLOGICAL SCIENCE

ECONOMIC GEOLOGY (Continued)

Elements of Petroleum Subsurface Engineering. By HAROLD VANCE. 1950. Pp. 168. Illus. 108. 4.25
Elements of Oil Reservoir Engineering. By SULVAIN J. PIRSON. 1954. Pp. 441. Illus. 225. 7.50
Oil Well Drainage. By S. C. HEROLD. 1941. Pp. 407. Figs. 15. 5.00
World Geography of Petroleum. Edited by W. E. PRATT and DOROTHY GOOD. 1950. Pp. 482. Illus. 9.00
North American and Middle East Oil Fields. By W. A. VER WIEBE. 1950. Pp. 260. Illus. 110. 6.00
Fundamentals of the Petroleum Industry. By DORSEY HAGER. 1939. Pp. 445. Cloth, 6 x 9. 7.00
Petroleum Production Economics. By LESTER CHARLES UREN. 1954. Pp. 614. Illus. 8.00
Petroleum Production Engineering. By LESTER C. UREN.
Vol. I. Oil Field Development. 1946. Pp. 764. 9.50
Vol. II. Oil Field Exploitation. 3rd Ed. 1953. Pp. 807. Illus. 367. 10.00
Vol. III. Petroleum Production Economics. 1950. Pp. 639. Illus. 117. 8.00
Science and Petroleum. By A. E. DUNSTAN, et al.
Vol. I. 1938. Pp. 836. Illus. Figs.
Vol. II. 1938. Pp. 1669. Illus. Figs.
Vol. III. 1938. Pp. 2385. Illus. Figs.
Vol. IV. 1938. Pp. 3192. Illus. Figs. Available as a set @ $60.00 (Vols. I–IV)
Vol. V. 1950. Pp. 200. Illus. Part I is available separately. 11.00
Natural Gas and Natural Gasoline. By R. L. HUNTINGTON. 1950. Pp. 598. 6 x 9. Illus. 267. 10.00
Encyclopedia of Hydrocarbon Compounds. Vol. X. $C_{11}H_8$ to $C_{11}H_{14}$. By JOSEPH E. Faraday. 1951. Pp. 270. 15.50
Oil Shales and Shale Oils. By H. S. BELL. 1948. Pp. 157. Illus. 5.00
Shale Oil (ACS Monograph No. 25). By RALPH H. MCKEE and 7 Collaborators. 1925. Pp. 326. Figs. 36. 6 x 9. 2.50
Petroleum Conservation. Edited by STUART E. BUCKLEY. 1951. Pp. 300. Illus. 6.00
Pegmatite Deposits of the White Picacho District, Maricopa and Yavapai Counties, Arizona. By RICHARD H. JAHNS. 1952. Pp. 105, pls. 24, figs. 5, tbls. 6. 1.25
The Conservation of Ground Water. By HAROLD E. THOMAS. 1951. Pp. 321. Illus. 6.50
Groundwater. By CYRUS F. TOLMAN. 1937. Pp. 593. Illus. 189. 9.00
The Geology of Water Supply. By CYRIL S. FOX. 1949. Pp. 209. Profusely illustrated. Cloth. 7.75
Applied Hydrology. By R. K. LINSLEY, JR., MAX A. KOHLER, and J. L. H. PAULHUS. 1949. Pp. 689. Illus. 328. 9.00
Hydrology. By OSCAR E. MEINZER. 1949. Pp. 723. Illus. 165. 4.95
Hydrology. By C. O. WISLER and E. F. BRATER. 1949. Pp. 419. Illus. 7.00
Elements of Applied Hydrology. By D. JOHNSTONE and W. P. CROSS. 1949. Pp. 276. Illus. 109. Tables 32. 5.00
Water and Man. By JONATHAN FORMAN and OLLIE E. FINK. 1950. Pp. 407. 4.50
A Practical Handbook of Water Supply. By FRANK DIXEY. 1950. Pp. 573; maps 6; figs. 133. 35s
Geology in Engineering. By JOHN R. SCHULTZ and ARTHUR B. CLEAVES. 1955. Pp. 592. Illus. 214. 8.75
Geology and Engineering. By ROBT. F. LEGGET. 1939. Pp. 650. Illus. Cloth, 6 x 9. 7.50
Geology for Engineers. By J. M. TREFETHEN. 1949. Pp. 620. Illus. 4.75
Geology for Engineers. 3rd Ed. By FRANCIS G. BLYTH. 1952. Pp. 336. Illus. 6.00
Elements of Engineering Geology. 2nd Ed. Revised (1947). By HEINRICH RIES and T. L. WATSON. Pp. 469. Illus. 293. 7.00
Geology Applied to Building and Engineering. By ARTHUR BRAY. 1948. Pp. 196. 18s
Applied Geology, a Symposium. By F. M. VAN TUYL and TRUMAN H. KUHN. Vol. 45, No. 1-B. 1950. Pp. 343. 3.00
Mineral Resources of the United States. By the STAFFS OF THE U. S. BUREAU OF MINES AND THE GEOLOGICAL SURVEY. 1948. Pp. 212. 5.00
Clays and Clay Technology. By JOSEPH A. PASK & MORT D. TURNER. 1955. Pp. 326. Bull. 164. 4.50
Refractories. 3rd Ed. By F. H. NORTON, 1949. 782 Pp. 419 Illus. 11.00
The Vermiculites and Their Utilization. By AUGUST GOLDSTEIN, JR. 1946. Pp. 64. 1.00
The Occurrence and Production of Vanadium. By G. O. ARGALL, JR. 1943. Pp. 56. 1.00
Foundation Engineering. By PECK, HANSON, and THORNBURN. 1953. Pp. 410. 8.00
Soil Mechanics in Engineering Practice. By KARL TERZAGHI and RALPH B. PECK. 1948. Pp. 566. 7.00
Soil Mechanics. 2nd Ed. By D. P. KRYNINE. 1947. Pp. 450. Illus. 7.00
Fundamentals of Soil Mechanics. By DONALD W. TAYLOR. 1948. Pp. 700. Illus. 239. 7.50
Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes. By M. JUUL HVORSLEV. 1949. Pp. 521. Illus. 450. 6.00
Introduction to Mine Surveying. By W. W. STALEY. 1939. Pp. 275. Illus. 3.75
A Mining Engineer's Survey Manual. By J. E. METCALFE. 1951. Pp. 341. 30s

GEOCHEMISTRY, CHEMICAL GEOLOGY

Geochemistry. By V. M. GOLDSCHMIDT edited by Alex Muir. 1954. Pp. 730, tbls. 96. 11.04
Principles of Geochemistry. By BRIAN MASON. 1952. Pp. 276. 5.50

(Continued on Page xiv)

(*Continued from Page xiii*)

BOOKS IN GEOLOGICAL SCIENCE

GEOCHEMISTRY, CHEMICAL GEOLOGY (Continued)

Isotope Geology. By KALERVO RANKAMA. 1955. Pp. 550 ..... 12.00
Nuclear Geology. By HENRY FAUL. 1954. Pp. 414 ..... 7.00
Geochemistry. By KALERVO RANKAMA and TH. G. SAHAMA. 1950. Pp. 900. Illus. 60 ..... 15.00
General Chemistry. 2nd Ed. By LINUS PAULING. 1953. Pp. 722. Illus. 193 including 2 color plates. Tables 33 ..... 6.50
The Physical Chemistry of the Silicates. By WILHELM EITEL. 1954. Pp. 1592, figs. 952 ..... 45.00
Silicate Analysis: A Manual for Geologists and Chemists, with Chapters on Check Calculations and Geo-Chemical Data. By A. W. GROVES and Foreword by ARTHUR HOLMES. 1951. Pp. 336 .... 5.50
Rocks for Chemists. An Introduction to the Study of Rocks from the Viewpoint of Chemistry. By S. J. SHAND. 1952. Illus. 4.50
Radiocarbon Dating. By WILLARD F. LIBBY. 1951. Pp. 122. Illus. 3.50
Spectrochemical Analysis. By L. H. AHRENS. 1st Ed. 2nd ptg. 1954. Pp. 354. Illus. 12.00
Wavelength Tables of Sensitive Lines. By L. H. Ahrens. 1st. Ed. 2nd ptg. 1954. Pp. 86 ..... 3.00

GEOPHYSICS, GEOPHYSICAL EXPLORATION

Advances in Geophysics. Volume I. By H. W. LANDSBERG. 1952. Pp. 362. XII. Illus. 8.50
Internal Constitution of the Earth. Edited by B. GUTENBERG. 1951. Pp. 439. Tables 88. Illus. 43 5.50
Introduction to Geophysical Prospecting. By M. B. DOBRIN. 1952. Pp. 435. Illus. 265 ..... 8.00
Exploration Geophysics. By J. JAY JAKOSKY. 1950. Pp. 1200 ..... 12.50
Applied Geophysics in the Search for Minerals. 4th Ed. By A. S. EVE and D. A. KEYS. 1954. Pp. 382 ..... 7.50
Practical Seismology and Seismic Prospecting. By L. D. LEET. 1938. Pp. 465 ..... 6.00
Seismic Prospecting for Oil. By C. HEWITT DIX. 1953. Pp. 414. Figs. 175 ..... 7.50
The Fundamentals of Electric Log Interpretation. By M. R. J. WYLLIE. 1954. Pp. 126. Illus. .. 3.60
Electrical Well Logging Fundamentals. By H. GUYOD. 1952. Pp. 164. Illus. 257 ..... 3.75
Geophysical Prospecting for Oil. By LEWIS L. NETTLETON. 1940. Pp. 444 ..... 7.00
Earth Waves. By L. DON LEET. 1950. Pp. 122. Illus. 69 ..... 3.90
Sonics. By THEODOR F. HUETER and RICHARD H. BOLT. 1955. Pp. 456. Illus. 231 ..... 10.00
The New Physics. By SIR C. V. RAMAN. 1951. Pp. 144 ..... 3.75

GEOMORPHOLOGY, PHYSICAL GEOLOGY, PHYSIOGRAPHY

Geographical Essays. By W. M. DAVIS. 1909. Republished unabridged, 1954. Pp. 777. Figs. 130 5.50
Physical Geology. By L. DON LEET and SHELDON JUDSON. 1954. Pp. 466 ..... 9.00
Physical Geology. 3rd Ed. By CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD F. FLINT. 1948. Pp. 602. Illus. 365 ..... 5.75
Visual Aids Kit 85.00
Introduction to Physical Geology. By C. R. LONGWELL and R. F. FLINT. Pp. 432. Figs. 308, Tbl. 12, Pls. 2 ..... 4.95
A Textbook of Geology. By R. M. GARRELS. 1951. Pp. 511 ..... 5.00
Principles of Geomorphology. By WILLIAM D. THORNBURY. 1954. Pp. 618. Figs. 275 ..... 8.00
Principles of Geology. By JAMES GILLULY, AARON C. WATERS, and A. O. WOODFORD. 1951. Pp. 640. Illus. 305 ..... 5.75
Geology. By VON ENGELN, O. E., and CASTER, K. E. 1952 ..... 7.50
General Principles of Geology. By J. F. KIRKLADY. 1955. Pp. 327. Pls. 6, Figs. 84 ..... 10.00
The Principles of Physical Geology. By V. E. MONNETT and H. E. BROWN. 1950. Pp. 450. Illus. 265 plus 16 topographic maps 4.75
Physical Geography. By A. H. STRAHLER. 1951. Pp. 442 ..... 6.75
Introduction to Geology. 3rd Ed. By E. B. BRANSON, W. D. KELLER, and W. A. TARR. 1952. Pp. 482. Illus. 6.00
The Earth as a Planet. GERARD P. KUIPER, Editor. 1954. Vol. II of the Solar System. Pp. 751 ..... 12.50
Geomorphology. 6th Ed. By CHARLES A. COTTON. 1952. Pp. 505. 473 Illus. 8.75
Geology. 4th Ed. By WM. H. EMMONS, THIEL, STAUFFER and ALLISON. 1955. Pp. 451. Illus. 6.50
Principles of Physical Geology. By ARTHUR HOLMES. 1945. Pp. 532. Pls. 95. Figs. 262 ..... 5.00
Physical Geology and Man. By KENNETH K. LANDES. 1948. Pp. 414. Figs. 164 ..... 6.65
Textbook of Geomorphology. 2d Ed. By PHILLIP G. WORCESTER. 1948. Pp. 584. Illus. Maps 6.25
Outlines of Physical Geology. 2nd Ed. By CHESTER R. LONGWELL, ADOLPH KNOPF, and R. F. FLINT. 1941. Pp. 387. Illus. 281 ..... 5.00
Geology. 3th Ed. By P. LAKE and R. H. RASTALL. 1941. Pp. 491. Figs. 129 ..... 5.25
Geomorphology. By A. K. LOBECK. 1939. Pp. 731. Fully Illus. 9.00
Introduction to Physical Geology with Special Reference to North America. 5th Ed. Revised by W. J. MILLER. 1949. Pp. 482. Illus. Maps 5.00

(*Continued on Page xv*)

(*Continued from Page xiv*)

BOOKS IN GEOLOGICAL SCIENCE

GEOMORPHOLOGY, PHYSICAL GEOLOGY, PHYSIOGRAPHY (Continued)

Outlines of Geology. 2nd Ed. Contains Outlines of Physical Geology. By CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD FLINT; and Outlines of Historical Geology by CHARLES SCHUCHERT and CARL O. DUNBAR. 1941. Pp. 672. Illus. 431 ..... 7.25

Laboratory Manual for Geology. By K. F. MATHER, C. J. ROY and L. R. THIESMEYER
Part I. Physical Geology (Revised). 1950. Pp. 165. Illus. 25 Line, 4 HT 2.75
Part II. Historical Geology. 1952. Pp. 252. Illus. 80 Line, 1 HT 2.75

Earth Science: The World We Live In. By SAMUEL N. NAMOWITZ and DONALD B. STONE. 1953. Pp. 438 ..... 3.96

Waves and Tides. By R. C. H. RUSSEL and D. H. MACMILLAN. 1953. Pp. 348. Pls. 17. Figs. 100 ..... 6.00

Dynamical Oceanography. By J. PROUDMAN. 1953. Pp. 409 ..... 8.50

The Tetons (Interpretations of a Mountain Landscape). By FRITIOF FRYXELL. 3rd printing, 1953. 92 Pp., 24 Illus. 2.00

The Incomparable Valley—A Geologic Interpretation of the Yosemite. By FRANCOIS E. MATTHES; edited by FRITIOF FRYXELL. 1950. Pp. 176, Frontis., 50 Illus. 11 Figs. 2 maps 3.75

Crater Lake (The Story of Its Origin). By HOWELL WILLIAMS, 3rd printing. 1954. 114 Pp., 25 Illus. 2.00

South African Scenery, A Textbook of Geomorphology. 2nd Rev. and Enlarged Edition. By L. C. KING. 1951. Pp. 412. Illus. 267 79 text figures, 1 folding map, 1 colored erosion map 6.37

Manual for Physical Geology. By PERCIVAL ROBERTSON. 1953. Pp. 101 ..... 2.50

Physiography of Eastern United States. By NEVIN M. FENNEMAN. 1938. Pp. 714. Illus. Cloth. 10.00

Physiography of Western United States. By NEVIN M. FENNEMAN. 1931. Pp. 534 ..... 9.00

The Physiographic Provinces of North America. By W. W. ATWOOD. 1940. Pp. 536. Illus. 281 .. 6.00

The Continental Shelf. By M. W. MOUTON. 1952. XII and 366 Pp. 6.50

The Oceans: Their Physics, Chemistry, and General Biology. By H. U. SVERDRUP, M. W. JOHNSON, and R. H. FLEMING. 1942. Pp. 1087 ..... 13.50

The Ocean. By F. D. OMMANNEY. 1949. Pp. 247. Pl. 4. Figs. 12. Bibliography. Maps 1.00

Submarine Geology. By FRANCIS PARKER SHEPARD. 1948. Pp. 348. Illus. 6.00

Marine Geology. By PH. H. KUENEN. 1950. Pp. 568. Illus. 250 ..... 8.00

The Ocean Floor. By HANS PETTERSSON. 1954. Pp. 181. Figs. 48 ..... 3.00

The Floor of the Ocean. By REGINALD ALDSWORTH DALY. 1942. Pp. 187. Figs. 82 ..... 3.00

Handbuch der Gletscherkunde und Glazialgeologie. By KLEBELSBERG. PROF. DR. R. 1948-49. 2 Bde. 40.00

Steam Blast Volcanic Eruptions. A Study of Mount Pelee in Martinique as Type Volcano. By THOMAS A. JAGGAR. 1949. Figs. 41 ..... 2.00

Volcanological Observations. By FRANK ALVORD PERRET. 1950. Quarto, Pp. 162. Figs. 117 ..... paper, $5.00

Catalogue of the Active Volcanoes of the World Including Solfatara Fields. Part I. Indonesia. By M. NEUMANN VAN PADANG. Ed. by the International Volcanological Assoc. 1951. Pp. 271. Figs. 117 ..... 5.00

Earth Beneath. By CHARLES A. COTTON. 1945. Pp. 128 ..... 2.25

Our Amazing Earth. By C. L. FENTON. Reissue 1945. Pp. 368. 39 pages halftones. 95 line drawings 4.75

Earth Sciences. By J. HARLEN BRETZ. 1940. Pp. 260. Illus. 122 ..... 3.00

METAMORPHIC, STRUCTURAL AND FIELD GEOLOGY

Metamorphism. A Study of the Transformation of Rock-Masses. 3rd Ed. By ALFRED HARKER. 1950. Pp. 362. Figs. 185. Cloth, 6 x 9 ..... 5.50

Principles of Structural Geology. 4th Ed. By C. M. NEVIN. 1949. Pp. 410. Illus. 250 ..... 6.00

Structural Geology. By MARLAND P. BILLINGS. 2nd Ed. 1954. Pp. 473. Figs. 336. Pls. 19 ... 10.00

Mountain Building. By REIN W. VAN BEMMELEN. 1954. Pp. 189, figs. 51 ..... 3.50

Structural Geology of North America. By A. J. EARDLEY. 1951. Pp. 624 ..... 12.50

The Tectonics of Middle North America. By PHILIP B. KING. 1951. Pp. 224. 52 Maps 3.75

Outline of Structural Geology. 3rd Ed. By E. S. HILLS. 1953. Pp. 170 ..... 3.50

The Dynamics of Faulting and Dyke Formation with Applications. 2nd Ed. By ERNEST M. ANDERSON. 1951. Pp. 216. Figs. 39 ..... 4.00

Field Geology. 5th ed. By F. H. LAHEE. 1952. Pp. 853. Illus. 5 x 7½ 9.50

Principles of Field and Mining Geology. By JAMES D. FORRESTER. 1946. Pp. 647. Illus. 316 .... 8.75

Structural Behavior of Igneous Rocks. By ROBERT BALK. Reprinted 1948. Pp. 187, Pl. 25 and 3 folded charts 4.25

The Use of Stereographic Projection in Structural Geology. By F. C. PHILLIPS. 1954. Pp. 86. Figs. 86 ..... 3.00

(*Continued on Page xvi*)

(Continued from Page xv)

BOOKS IN GEOLOGICAL SCIENCE

METEOROLOGY AND CLIMATE

The Climate Near the Ground. By R. GEIGER. 1950. Pp. 482. Figs. 181. Tables 63..... 6.00

The Atmospheres of the Earth and Planets. Rev. Ed. By GERARD P. KUIPER. 1952. Pp. 416 .....Paper $5.50; Cloth 8.50

Cloud Physics. By D. W. PERRIE. 1951. Pp. 119. Pls..... 4.50

Weather Elements. 3rd Ed. By T. A. BLAIR. 1948. Pp. 373..... 6.35

Descriptive Meteorology. By HURD C. WILLETT. 1952. Pp. 310. VIII 6.00

Dynamic Meteorology. By HOLMBOE, FORSYTHE and GUSTIN. 1945. Pp. 378. Illus. 222..... 6.00

General Meteorology. By HORACE R. BYERS. 1944. Pp. 645. Illus. 284. Tables 27..... 7.50

Meteorology, Theoretical and Applied. By E. W. HEWSON and R. W. LONGLEY. 1944. Pp. 468. Illus. 193..... 7.00

Handbook of Meteorology. By FREDERIC A. BERRY, E. BALLAY and N. R. BEERS. 1945. Pp. 1116 13.50

Climatology. By BERNARD HAURWITZ and JAMES M. AUSTIN. 1944. Pp. 410..... 8.00

Climatology. By T. A. BLAIR. 1942. Pp. 484..... 7.65

Techniques of Observing the Weather. By BENARTHUR C. HAYNES. 1947. Pp. 272. Illus. 98.... 4.90

Air Pollution: Proceedings of the U. S. Technical Conference on Air Pollution. By L. C. MCCABE. 1952. Pp. 847..... 12.50

MINERAL ECONOMICS, GEOPOLITICS

Minerals in World Industry. By WALTER H. VOSKUIL. 1955. Pp. 316. Tables 38. Figs. 26.... 5.75

The Mineral Resources of the World. By VAN ROYEN and BOWLES. 1952. Volume II. Pp. 180. Figs. 186..... 12.00

Conservation of Natural Resources. Ed. by GUY-HAROLD SMITH. 1950. Pp. 552. Illus..... 6.75

The Future of Our Natural Resources. Volume 281 of The Annals of the American Academy of Political and Social Science. By STEPHEN RAUSHENBUSH. May, 1952. Pp. 275..... 2.00

The Earth and Its Resources. 2nd Ed. By V. C. FINCH, G. T. TREWARTHA, and M. H. SHEARER. 1948. Pp. 584. Illus. 463..... 4.80

Out of the Earth. By G. B. LANGFORD. 1954. Pp. 140, pls. 14, figs. 28, tbls. 3 ..... 3.50

Natural Resources Utilization in a Background of Science and Technology. Vol. 1: Geology and Geography. By JAMES C. MALIN. 1950. Pp. 377. Illus. 5. Lithoprint from typescript, paper cover 2.50

The Agricultural Resources of the World. By WM. VAN ROYEN. 1954. Pp. 258. Figs. 338 (Vol. I of Atlas of World Mineral Resources) 13.35

Resource Conservation: Economics and Policies. By CIRIACY-WANTRUP. 1952. Pp. 396..... 6.50

World Population and Future Resources. The Proceedings of the Second Centennial Academy Conference of Northwestern University, Evanston, Ill. By P. K. HATT. 1952. Pp. 280 ..... 3.50

Conservation in the United States. 3rd Ed. By GUSTAFSON, GUISE, HAMILTON, JR., and RIES (Members of the faculty of Cornell University). 1949. Pp. 543. Tables 21..... 5.00

A Conservation Handbook. By SAMUEL H. ORDWAY, JR. 1949. Pp. 76..... 1.00

Economics of Natural Gas in Texas. By J. R. STOCKTON, R. C. HENSHAW, JR. and R. W. GRAVES. 1952. Pp. 316. Pls. 38. Figs. 19. Tables 87..... 5.00

Arabian Oil—America's Stake in the Middle East. By RAYMOND F. MIKESELL and HOLLIS B. CHENERY. 1949. Pp. 216. 19 tables..... 3.50

Minerals in World Affairs. By THOMAS S. LOVERING. 1943. Pp. 394. Tables 50...$4.75 to schools 6.35

Energy Sources—The Wealth of the World. By EUGENE AYRES and CHARLES A. SCARLOTT. 1952. Pp. 344..... 5.00

World Minerals and World Peace. By CHARLES K. LEITH, J. W. FURNESS and CLEONA LEWIS. 1943. Pp. 253. Pls. 15. Tables 41..... 2.50

Strategic Materials in Hemisphere Defense. By M. S. HESSEL, W. MURPHY, and F. A. HESSEL. 1942. Pp. 235. Illus. 20..... 2.50

Minerals—A Key to Soviet Power. By DEMITRI B. SHIMKIN. 1953. Pp. 452. Figs. 8. Tables 101 8.00

Seventy-five Years of Progress in the Mineral Industry (1871–1946) American Institute of Mining and Metallurgical Engineers. By A. B. PARSONS, *Editor*. 1947. Pp. 817..... 5.00

MINING

Elements of Mining. 4th Ed. By G. J. YOUNG. 1946. Pp. 755. Illus. 382..... 8.50

The Basis of Mine Surveying. By M. H. HADDOCK. 1952. Pp. 301. Fig. 246..... 4.20

Mining Year Book. By WALTER E. SKINNER. 1953. Pp. 856..... 7.00

Mines Register, 1952 Rev. Ed. Successor to **The Mines Handbook (Descriptions of mines and mining companies).** Pp. 730..... 25.00

Handbook for Prospectors and Operators of Small Mines. 4th Ed. By MAX W. VON BERNEWITZ—Revised by HARRY C. CHELLSON. 1943. Pp. 547. Illus. 161. 5 x 7½..... 7.50

Mining Engineer's Handbook. By ROBERT PEELE, *Editor*. 3d Ed. 1941. 2 Vols..... 18.50

Examination and Valuation of Mineral Property. By ROLAND D. PARKS. 3d Ed. 2nd ptg., 1952. Pp. 504. Illus..... 9.00

(Continued on Page xvii)

(*Continued from Page xvi*)

BOOKS IN GEOLOGICAL SCIENCE

PALEONTOLOGY, STRATIGRAPHY, HISTORICAL GEOLOGY

Historical Geology. By CARL O. DUNBAR. 1949. Pp. 567. Illus. 380 ..... 6.50

Introduction to Historical Geology. By RAYMOND C. MOORE. 1949. Pp. 582. Illus. Maps..... 6.75

Historical Geology. By RAYMOND C. MOORE. 1933. Pp. 673. Figs. 413 ..... 3.50

Historical Geology—The Geologic History of North America. 2nd Ed. By RUSSELL C. HUSSEY. 1947. Pp. 465. Illus. 344 ..... 5.75

Geology: An Introduction to Earth History. By H. H. READ. 1949. Pp. 256. Illus. 30. Maps... 1.00

The Principles of Historical Geology. By J. WILLIS STOVALL and H. E. BROWN. 1954. Pp. 472. Illus. 200 ..... 6.00

An Introduction to Historical Geology. 6th Ed. By W. J. MILLER. 1952. Pp. 555. Illus..... 5.50

Dating the Past—An Introduction to Geochronology. 2nd Ed. By FREDERICK E. ZEUNER. 1950. Pp. 450, figs. 46; tbls. 57; pls. 24 ..... 5.50

The Origin and History of the Earth. By ROBERT TUNSTALL WALKER and WOODVILLE JOSEPH WALKER. 1954. Pp. 244. Illus., Figs....U.S., 5.00; Canada & Mexico, 5.25; Other Countries 5.50

The Planets: Their Origin and Development. By HAROLD C. UREY. 1952 ..... 5.00

The Origin of the Earth. By W. M. SMART. 1951. Pp. 239 ..... 3.50

Geology and Man. By KENNETH K. LANDES and RUSSELL C. HUSSEY. 1948. Pp. 518. Figs. 188. 7.65

Introduction to College Geology. By CHAUNCEY D. HOLMES. 1949. Pp. 429; figs. 312; tables.... 4.50

Glacial Geology and the Pleistocene Epoch. By RICHARD F. FLINT. 1947. Pp. 589. Illus. 94.... 9.00

Outlines of Historical Geology. 4th Ed. By CARL O. DUNBAR and CHARLES SCHUCHERT. 1941. Pp. 291. Illus. 176 ..... 4.50

Record of the Rocks. By HORACE G. RICHARDS. 1953. Pp. 413. Figs. 294 ..... 6.00

An Introduction to Stratigraphy. 2nd Edition, revised. By L. D. STAMP. 1950. Pp. 381 ..... 2.25

Stratigraphic Geology. By MAURICE GIGNOUX. 1955. Pp. 830. Fig. 155 ..... 9.50

Principles of Invertebrate Paleontology. By R. P. SHROCK and W. H. TWENHOFEL. 2nd Ed. 1953. Illus. 488. Pp. 785 ..... 12.00

Outlines of Paleontology. 3rd Ed. By H. H. SWINNERTON. 1947. Pp. 385. Figs. 368 ..... 6.50

Index Fossils of North America. By HERVEY W. SHIMER and ROBERT P. SHROCK. 1944. Pp. 837. Illus. 8,000. Pls. 303 ..... 22.00

Invertebrate Fossils. By R. MOORE, C. LALICKER and A. FISCHER. 1952. Illus. 454. Pp. 738.... 12.50

Invertebrate Palaeontology. 3th Ed. Rev. and Enl. By HENRY WOODS. 1946. Pp. 477. Figs. 221 3.50

Evolution of the Vertebrates. By EDWIN H. COLBERT. 1955. Pp. 479. 125 Illus.... ..... 8.95

Paleontology and Modern Biology. By D. M. S. WATSON. 1951. Pp. 216. Figs. 77 ..... 4.00

Natural History of Marine Animals. By MACGINITIE and MACGINITIE. 1949. 473 Pp., 282 Illus. 7.50

***Principles of Micropaleontology.** By MARTIN F. GLAESSNER. 1947. Pp. 296. Illus..... 6.00

Foraminifera: Their Classification and Economic Use. 4th Ed., Revised and Enlarged. By JOSEPH A. CUSHMAN. 1948. Pp. 605. Figs. 9. 31 Text Pls. 55 Key Pls..... 12.50

The Invertebrates: Platyhelminthes and Rhynchocoela. The Acoelomate Bilateria, Vol. II. By LIBBIE HENRIETTA HYMAN. 1951. Pp. 550. 208 figs..... 9.00

A Textbook of Evolution. By EDWARD O. DODSON. 1952. Pp. 419. Illus. 101 ..... 5.00

Evolution Emerging. By W. K. GREGORY. 1951.
Vol. I. Pp. 736. Vol. II. Pp. 1013 .....Boxed set of two volumes. 20.00

The Meaning of Evolution, A Study of the History of Life and its Significance for Man. By G. G. SIMPSON. 1950. Pp. 364. Illus..... 4.00

The Principles of Classification and a Classification of Mammals. By G. G. SIMPSON. 1945. Vol. 85. Pp. 350 ..... 3.50

Genetics Paleontology and Evolution. By G. L. JEPSEN, ERNST MAYR, and GEORGE G. SIMPSON (ed.). 1949. Pp. 448. Illus..... 7.50

History of the Primates. 2nd Ed. By W. E. LE GROS CLARK, F.R.S. 1950. Pp. 118. 40 text-figures..... .80

The Dinosaur Book: The Ruling Reptiles and Their Relatives. By E. H. COLBERT. 1951. Pp. 156. Illus..... 5.00

On the Origin of Species. By CHARLES DARWIN. Reprinted 1951 of 1859 Edition. Pp. 426..... 3.75

Man, the Tool-Maker. 2nd Ed. By K. P. OAKLEY. 1950. Pp. 98. 41 text-figures..... 1.00

Strange Story of our Earth. By A. H. VERRILL. 1952. Pp. 255. Illus. 72 ..... 3.75

The Succession of Life through Geological Time. By K. P. OAKLEY and H. M. MUIR-WOOD. 2nd Ed. 1949. Pp. 92. Pls. 12 and 4 maps..... 2s 6d

Life Through the Ages. By CHARLES R. KNIGHT. 1946. Pp. 66..... 2.50

Life Through the Ages. By R. W. BURNETT. 1947. Pp. 48. Illus..... 1.00

Introduction to Paleobotany. By CHESTER A. ARNOLD. 1947. Pp. 433..... ..... 8.00

An Introduction to the Study of Fossil Plants. By JOHN WALTON. 1940. Pp. 188. Illus..... 4.75

Procedure in Taxonomy. By E. T. SCHENK and J. H. MCMASTERS. Revised Ed. 1948. Pp. 93.. 2.50

Examination of Well Cuttings. By JULIAN W. LOW. 48 Pp. 13 schematic illustrations. 1952.... 1.50

(*Continued on Page xviii*)

(*Continued from Page xvii*)

BOOKS IN GEOLOGICAL SCIENCE

PETROLOGY, SEDIMENTATION

A Descriptive Petrography of the Igneous Rocks. 1931–38. By A. JOHANNSEN.
Vol. I—Introduction, Textures, Classifications, and Glossary. Rev. Ed. 1939. Pp. 318 ..... 6.00
Vol. II—The Quartz-Bearing Rocks. 1932. Pp. 438. Diagrams 9. Photographs 16. Photomicrographs 66. Portraits 32. Tables 209 ..... 8.00
Vol. III—The Intermediate Rocks. 1937. Pp. 360. Diagrams 4. Photographs 18. Photomicrographs 114. Portraits 47. Tables 108 ..... 7.00
Vol. IV—Part I. The Feldspathoid Rocks; and Part II. The Peridotites and Perknites. 1938. Pp. 551. Diagram 8. Photographs 9. Photomicrographs 95. Portraits 77. Tables 159. 10.00

Textbook of Petrology.
Vol. 1: The Petrology of the Igneous Rocks. 10th Ed. By F. H. HATCH, A. K. WELLS, and M. K. WELLS. 1950. Pp. 469 ..... 4.50
Vol. 2: The Petrology of the Sedimentary Rocks. 3rd Ed. revised by MAURICE BLACK. 1938. By F. H. HATCH and R. H. RASTALL. 1913. Reprinted 1950. Pp. 383. Illus. 75. Tables 15. 4.50

Petrography. Part I—Igneous Rocks; Part II—Metamorphic Rocks; Part III—Sedimentary Rocks. By HOWEL WILLIAMS, FRANCIS J. TURNER and CHARLES M. GILBERT. 1954. Pp. 416. 133 Illus. 6.50

Gesteine und Minerallagerstatten, Allgemeine Lehre von den Gesteinen und Minerallagerstaatten. By PAUL NIGGLI. 1952. Pp. 534. Figs. 181
Vol. I 11.65
Vol. II 11.65

Einfuhrung in die gesteinkunde. By H. LEITMEIER. 1930. Pp. 275 ..... 5.00

Igneous and Metamorphic Petrology. By F. J. TURNER and J. VERHOOGEN. 1951. Pp. 490 ..... 9.50

The Origin of Metamorphic and Metasomatic Rocks. By HANS RAMBERG. 1953. Pp. 352. Illus. 130 charts, graphs, photographs and line drawings 10.00

Theoretical Petrology. By T. F. W. Barth. 1952. Pp. 387. Illus. 6 x 9¼ 7.00

Introduction to Theoretical Igneous Petrology. By ERNEST E. WAHLSTROM. 1950. Pp. 365; numerous figs. and tables 6.50

A Historical Survey of Petrology. By F. J. LOEWINSON-LESSING translated by S. I. TOMKIEFF. 1954. Pp. 112 ..... 2.25

Petrographic Mineralogy. By ERNEST E. WAHLSTROM. 1955. Pp. 408 ..... 7.75

Rocks and Rock Minerals. By LOUIS V. PIRSSON and ADOLPH KNOPF. 1947. Pp. 349. Pls. 36. Figs. 72 ..... 6.00

Rocks and Mineral Deposits. By PAUL NIGGLI (English Translation by ROBERT L. PARKER). 1954. Pp. 572. Figs. 331, tbls. 73 ..... 12.00

Les Pegmatites—Les Pegmatites Granitiques. By A. E. FERSMAN. 1951. Pp. 675.
Vol. I—Partie Preliminaire. Chaps. 1–10
Vol. II—Partie Descriptive. Chaps. 11–18
Vol. III—Partie Generale. Chaps. 19–25 ..... 18.00

Eruptive Rocks. 3rd Ed. By S. JAMES SHAND. 1948. Pp. 488. Illus. 55 ..... 7.50

The Study of Rocks. 4th Ed. By S. J. SHAND. 1951. Pp. 236 ..... 2.25

Igneous Minerals and Rocks By ERNEST E. WAHLSTROM. 1947. Pp. 367. Illus. 6.50

Structural Petrology of Deformed Rocks. 2nd Ed. 2nd Ptg. By HAROLD W. FAIRBAIRN and FELIX CHAYES. 1954. Pp. 344; numerous figs. and tables 12.50

Petrography and Petrology. By FRANK F. GROUT. 1932. Pp. 522 ..... 7.50

Igneous Rocks and the Depths of the Earth. 2nd Ed. By REGINALD A. DALY. 1933. Pp. 598 ... 11.00

Minerals and Rocks. By RUSSELL D. GEORGE. 1943. Pp. 595. Figs. 150. Pls. 48 ..... 6.00

Photomicrography. By CHARLES P. SHILLABER. 1944. Pp. 773. Illus. 291 ..... 15.00

Applied Sedimentation. A Symposium edited by PARKER D. TRASK. 1950. Pp. 707. Illus. 134 ... 7.50

Principles of Sedimentation. 2nd Ed. By W. H. TWENHOFEL. 1950. Pp. 673. Figs. 81 ..... 8.50

Methods of Study of Sediments. By W. H. TWENHOFEL and S. A. TYLER. 1941. Pp. 183. Illus. 4.50

Sedimentary Rocks. By F. J. PETTIJOHN. 1949. Pp. 524. Pls. 40 ..... 7.50

Stratigraphy and Sedimentation. By W. C. KRUMBEIN and L. O. SLOSS. 1951. Pp. 507. Illus. 123. Line Drawing 5.50

Sedimentary Petrography. By HENRY B. MILNER. Reprint of Third edition. 1940. 666 Pp. with new Preface and Corrigenda 9.50

The Composition and Origin of the Antrim Laterites and Bauxites. By V. A. EYLES. 1952. Pp. 90, pls. 2, tbls. 10 ..... 12s6d

Problems of Clay and Laterite Genesis. By AIME. 1952. Pp. 252. AIME Members 4.20
Nonmembers 6.00

Abrasion Hardness. By THOMAS A. JAGGAR. 1950. Pp. 43. Pl. 6. Figs. 5. Tables 7 ..... 1.00

(*Continued on cover 3*)

(Continued from Page xviii)

BOOKS IN GEOLOGICAL SCIENCE

PETROLOGY, SEDIMENTATION (Continued)

An Introduction to the Study of Organic Limestones. By J. Harlan Johnson. Rev. Ed. 1951. Pp. 183. Illus. 104 ..... 2.00

An Introduction to the Study of Rock Building Algal Limestones. By J. Harlan Johnson. Pp. 117. Illus. 63 ..... 2.50

Sequence in Layered Rocks. By Robert R. Shrock. 1948. Pp. 307 ..... 8.50

Manual of Sedimentary Petrography. By Krumbein and Pettijohn. 1938. Pp. 549. Figs. 262. 6.50

Micromeritics, The Technology of Fine Particles. 2nd Ed. By Joseph M. Dalla Valle. 1948. Pp. 555. Figs. 131 ..... 10.00

The Rock Book. By C. L. Fenton and M. A. Fenton. 1940. Pp. 376. 48 pp. Photo. 40 figs. ... 7.50

Soil. By G. V. Jacks. 1955. Pp. 221. Pls. 10. Figs. 5 ..... 5.00

Factors of Soil Formation. By Hans Jenny. 1941. Pp. 281 6 x 9 Illus. 5.50

A Bibliography on Meteorites. By Harrison Brown, Editor. 1953. Pp. 686 ... .10.00

HISTORICAL AND BIOGRAPHICAL

The Life and Times of Alexander von Humboldt, 1769–1859. By Helmut De Terra. 1955 ..... 5.75

The Birth and Development of the Geological Sciences. By F. D. Adams. 1955. Pp. 511, Illus. 91 1.95

Blazing Alaska's Trails. By Alfred H. Brooks. 1953 ..... 4.50

Life and Letters of R. A. F. Penrose, Jr. By Helen R. Fairbanks and Charles P. Berkey. 1952. Pp. 765 ..... 4.00

Giants of Geology. By Carroll and Mildred Fenton. 1952. Pp. 333. Illus. 3.75

The Growth of Physical Science. 2nd Ed. By Sir James Jeans. 1951. Pp. 364. Pls. 14 ..... 3.75

Evolutionary Thought in America. Edited by Stow Persons. 1950. Pp. 463 ..... 5.00

De Re Metallica. By Georgius Agricola. 1950 translation of the 1912 edition from the latin by Herbert Hoover and Lou Henry Hoover. Pp. 672 ..... 10.00

Giordano Bruno—His Life and Thought. With Annotated Translation of his Work on the Infinite Universe and Worlds. By Dorothea Waley Singer. 1950. Pp. 404. Illus. 6.00

Benjamin Silliman, Pathfinder in American Science. By John F. Fulton and Elizabeth H. Thomson. 1947. Pp. 312 ..... 4.00

Journal of Research into the Geology and Natural History of the Various Countries Visited by H.M.S. Beagle. 1952. Pp. 615; pls. 16 (reprint of first editon, 1839) 7.50

Powell of the Colorado. By W. C. Darrah. 1951. Pp. 426 ..... 6.00

The Bonanza Trail, Ghost Towns and Mining Camps of the West. By Muriel Sibell Wolle. 1953. Pp. 476, figs. 108, maps 14 ..... 8.50

PHOTOGRAMMETRY, TOPOGRAPHY

Elements of Cartography. By Arthur H. Robinson. 1953. Pp. 254. Figs. 186. Tables 38 ..... 7.00

Plane Table Mapping. By J. W. Low. 1951. Pp. 365 ..... 4.50

Handbook of Aerial Mapping and Photogrammetry. By L. G. Thorpe. 1952. 2nd ed. rev. Pp. 80 6.00

Manual of Photogrammetry. 2nd Ed. 1952. Pp. 876 ..... 12.50

Aerial Photographs and Their Application. By Harold T. U. Smith. 1943. Pp. 372. Figs. 61 .... 4.50

Military Maps and Air Photographs. By Armin K. Lobeck and W. J. Tellington. 1944. Pp. 256. Illus. 8½ x 11 ..... 7.00

Essentials of Aerial Surveying and Photo Interpretation. By Talbert Abrams. 1944. Pp. 259. Maps 3.50

TECHNICAL DICTIONARY, TERMINOLOGY, THESAURUS

Multilingual Mining—Metallurgical—Geological—Mineralogical—Petrographical and Petroleum Dictionary. English-Spanish, French, German, and Russian. By Alejandro Novitsky. 1951. Pp. 369 ..... 12.00

German-English and English-German Dictionary for Scientists. By O. W. Leibiger and I. S. Leibiger. 1950. Pp. 752 ..... 8.00

German-English Technical and Engineering Dictionary. By Louis deVeries. 2nd Ed. 1950. Pp. 940 ..... 20.00

German-English Technical Dictionary. 2 Volumes. By Kurt F. Leidecker (ed.), Compiled by U. S. Air Force. 100,000 terms 35.00

English-French and French-English Technical Dictionary. By Francis Cussey. 1946. Pp. 590 ... 5.00

Geology and Allied Sciences. A thesaurus and coordination of English and German terms. Pt. I. German-English. Walter Huebner, Ed. Pp. 434. 1939. Cloth, 5½ x 8½ 7.50

Dictionary of Scientific Terms. 5th Ed. By John H. Kennedy. 1953 ..... 12.50

(Continued on cover 4)

(*Continued from cover 3*)

BOOKS IN GEOLOGICAL SCIENCE

TECHNICAL DICTIONARY, TERMINOLOGY, THESAURUS (Continued)

The Russian-English Technical and Chemical Dictionary. By LUDMILLA I. CALLAHAN. 1947. Pp. 794 ..... 15.00
Scientific Russian. By J. W. PERRY. 1951. Pp. 845 ..... 10.00
Van Nostrand's Scientific Encyclopedia. 2nd Ed. 1947. Pp. 1600 ..... 17.50
Webster's Geographical Dictionary. 1949. Pp. 1352. 177 maps, 24 color plates 8.50
Pocket Dictionary of Meteorology. By DR. KARL KEIL. 1950. Pp. 604 with numerous Illus. 7.00

MISCELLANEOUS

Man's Nature and Nature's Man. By LEE R. DICE. 1955. Pp. 329 ..... 5.00
Man's Emerging Mind. By N. J. BERRILL. 1955. Pp. 308 ..... 4.00
Conversation with the Earth. By HANS CLOOS. 1953. Pp. 413. Pls. 53. Tables 36 ..... 5.75
Man, Time and Fossils. By RUTH MOORE. 1953. Pp. 411, figs. 71, pls. 62 ..... 5.75
Man and His Physical Universe. By RICHARD WESTAR. 1953. Pp. 488. Illus. 300 ..... 4.75
Guide to Geologic Literature. By RICHARD M. PEARL. 1951. Pp. 239 ..... 5.50
Fundamentals of Earth Science. By HENRY D. THOMPSON. 1947. Pp. 420 ..... 4.00
Symphony of the Earth. By J. H. F. UMBGROVE. 1951. Pp. 220. Pls. 10. Figs. 123 ..... 5.00
Readings in the Physical Sciences. By HARLOW SHAPLEY (ed.). 1948. Pp. 501 ..... 3.00
Writing the Technical Report. 3rd Ed. By J. R. NELSON. 1952. Pp. 388 ..... 4.50
Volcanoes Declare War. By THOMAS A. JAGGAR. 1945. Pp. 166. Pl. 32. Figs. 34 ..... 4.85
Volcanoes New and Old. By MRS. SATIS N. COLEMAN. 1946. Pp. 234 ..... 4.75
Rocks and Rivers of North America. By ELLIS W. SHULER. 1945. Pp. 300 ..... 4.00
Friendly China. By BAILEY WILLIS. 1949. Pp. 312 ..... 3.00
Astronomy of Stellar Energy and Decay. By MARTIN JOHNSON. 1951. Pp. 216. Figs. 22 ..... 3.50
The Earth and the Stars. 2nd Ed. By C. G. ABBOTT. 1946. Pp. 288. Illus. 3.50
This Earth of Ours—Past and Present. By CALEB W. WOLFE. 1950. Pp. 384. Illus. 5.00
The Face of the Moon. By R. B. BALDWIN. 1949. Pp. 226. Illus. 5.00
Measuring Our Universe. By O. J. LEE. 1950. Pp. 170. Illus. 45 ..... 3.25
The Religion of the Modern Scientist. By Dr. S. W. TROMP. 1951. Pp. 480. Illus. 113. Tables 3 5.50

Address ECONOMIC GEOLOGY, Urbana, Ill. Books not in this list (except the publications of official Surveys and those of the Geological Society of America) will be furnished at Publisher's prices. Also consult more extended lists in volume 50.

Economic Geology Publishing Company will also attempt to secure past volumes of domestic and foreign geological journals and similar publications when contained in our file listings of secondhand book dealers. Special correspondence in search of material however can not be undertaken.